Torrent erosion in Lake District mountain catchments.

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TORRENT EROSION IN LAKE DISTRICT MOUNTAIN CATCHMENTS

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PULLOUTS

ABSTRACT

This thesis investigates torrent erosion in Lake District mountain catchments, Northern England. A nested research approach was used. Detailed investigations were undertaken at two case study sites (Iron Crag, Raise Beck) together with a survey of torrents across the Skiddaw and Helvellyn massifs.

At Iron Crag an annual sediment budget was constructed by monitoring hillslope, channel and fan processes. Particle size characteristics of sediments, and the history of fan development were investigated. Results show channel and bank sediments are the main source of material supplied to the fan. Large rainfall events cause significant change in the channel, banks and fan. The impact of different meteorological conditions on sediment characteristics is complex, however a seasonal cycle of sediment production (winter) and exhaustion (autumn) exists. Historically, initial fan aggradation predates 36 BC, but a rapid phase of deposition began between 1200-1400 AD. Investigations at Raise Beck focussed on a flood that occurred in January 1995 and caused channel avulsion and shallow landsliding. This was reconstructed using a range of geomorphological and sedimentological evidence. Palaeohydrological methods give a discharge between 27- 74 $m^3 s^{-1}$, whereas as rainfall-runoff values range between 4 - 6 $m^3 s^{-1}$. The magnitude of the 1995 flood was smaller than two 19th Century events, but would still exceed the capacity of contemporary engineered channels.

The regional survey considered the characteristics and importance of torrents, mountain streams, and debris flows; and provided a context for work at the case study sites. The case study sites are distinct members of the regional populations. Raise Beck being the largest (133 ha) and highest (858 m O.D.); Iron Crag amongst the smallest (2.4 ha) and lowest (600 m O.D.). Overall, torrents and hillslope debris flows are minor components of the landscape (aerially 2.1 % Helvellyn massif, 0.4 % Skiddaw massif). Sites are preferentially located in regard to altitude and slope. Debris flows are related to geological type. Large torrent floods are relatively rare and can be broadly related to regional flood episodes. Contemporary debris flow activity is of low magnitude and frequency.

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This thesis is dedicated to my parents who have provided me with continuing support and opportunity in my pursuit to keep digging holes, and to get wet and dirty.

I confirm that no part of the material presented in this thesis has previously been submitted by me or any other person for a degree in this, or any other University. In all cases, where it is relevant, material from the work of others has been acknowledged.

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CHAPTER 1: INTRODUCTION

1.0 Scope of chapter

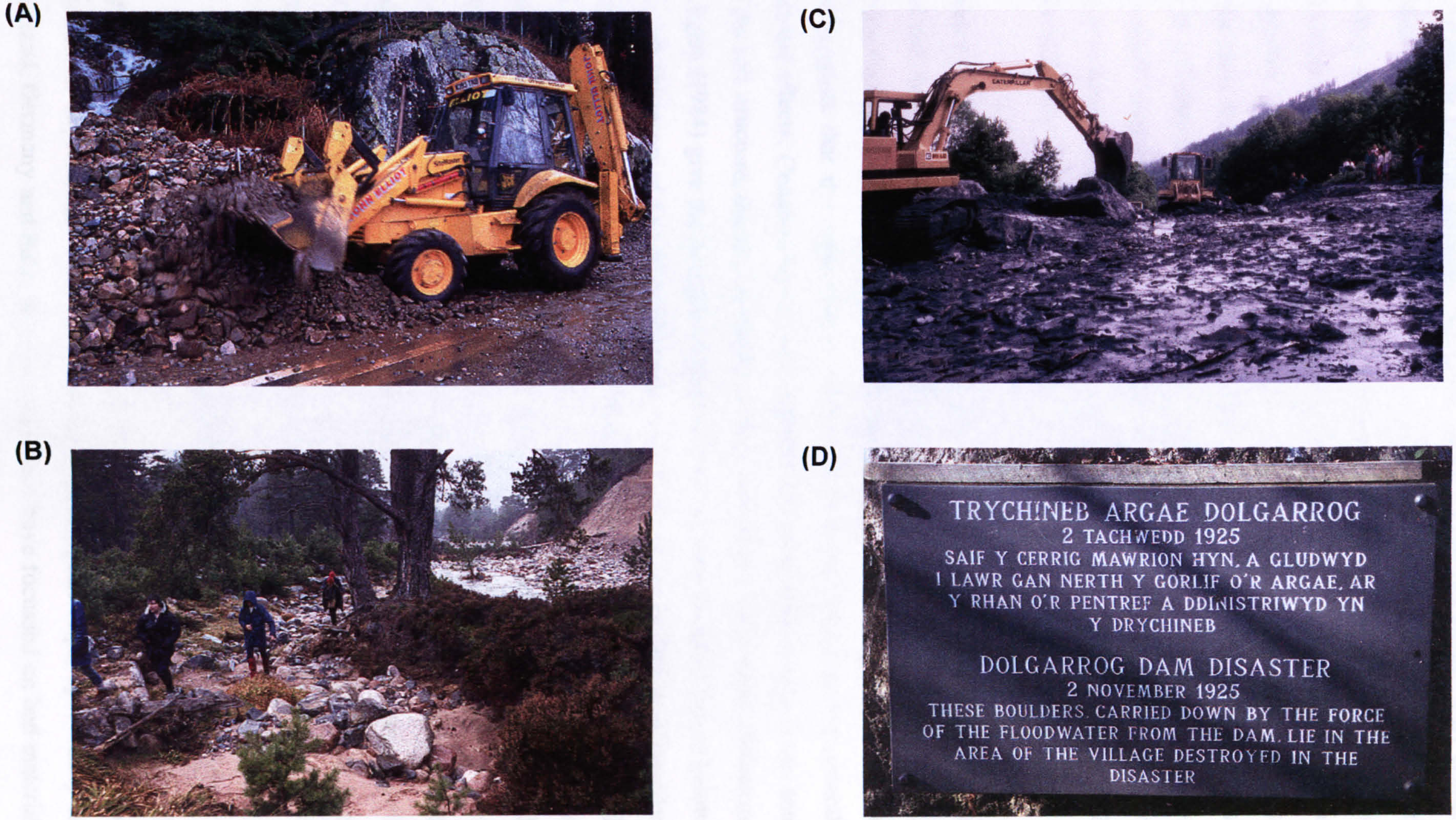
This chapter provides an introduction to the topic of torrent erosion processes and the thesis investigations that follow. Sectio[n 1.1 briefly describes mountainous catchments, their importance, and the significance of flooding. Section 1.2 briefly considers research that has been undertaken on torrents, both in Europe and the UK. Section 1.3 states the research aim and general objectives of this study, and section 1.4 considers how these objectives are operationalised in the study area. Finally, section 1.5 outlines the thesis structure, providing a short description of the contents of each chapter.

1.1 The nature of mountainous catchments

Upland and mountain catchments are characterised by steep gradients, high relative relief, and sharp climatic and biotic gradients (Barsch and Caine, 1984; Becker and Bugmann, 1997). In these environments geomorphological processes are generally more active than in nearby lowland locations (Barsch and Caine, 1984), since the occurrence of high magnitude events is more common. Geomorphological processes in upland and mountain catchments can be categorised according to the process type (e.g. Caine, 1974; Boardman, 1992) and the morphological features created in association with these processes (e.g. Ballantyne and Harris, 1994). Landform features occupy either hillslopes, the drainage system, or involve a combination of both. Hillslope features include slow mass movement forms associated with soil creep and solifluction, such as terracettes and solifluction lobes, and slope scars due to shallow landsliding. Rapid mass movements include rockfall, which when deposited results in talus, and debris flows, which produce a suite of landforms including a source scar, flow track and depositional levees and lobes. Drainage forms include small gullies developed on hillslopes, and more significant features occupying valley axes, such as streams, torrents and rivers. Mountain streams and torrents both have steep, step-pool channels, with abundant sediment supply, flashy flow and sediment transport regimes (Newson, 1981; Eisbacher and Clague, 1984). Both streams and torrents are important components of mountain catchments as they enable the swift transfer of material from hillslopes, and water from higher to lower elevations. Torrents are characterised by having a range of sediment-water flows, i.e. Newtonian water flows, and non-Newtonian viscous flows such as debris flows (Jaeggi, 1995; Rickenmann, 1997). Mountain streams tend to be dominated by fluvial flows (Eisbacher and Clague, 1984).

The erosion and flooding of torrents and streams is of great importance in the mountains and uplands. Schmidt and Ergenzinger (1994, p3) suggest the unsystematic arrangement of torrents makes them highly incalculable and poses many problems for water management and flood control as well as for discharge, sediment yield and hazard determination. This is especially so when viewed against a background of increasing human activities in high mountain areas. These catchments receive large annual rainfall totals and act as an important water resource (e.g. Wilhem, 1994). Hence sediment load is an issue in terms of water quality, as particulate and mineral components require treatment, and sediment transport affects the operational life of water storage reservoirs (Butcher *et al.,* 1992; Butcher *et al.*, 1993, White *et al.,* 1996). Secondly, flooding of watercourses is a hazard in many upland areas. Out-of-channel flows of water and sediment cause disruption and damage to nearby infrastructure, such as the blockage of roads and damage to buildings e.g. Raise Beck flood of January 1995 (this study) (Figure 1 a); the Mill Gill flood of August 1749 (Carling, 1997). Agriculture also suffers with the destruction of walls, the loss of livestock, and sediment deposits spread over pasture land e.g. Langdale floods of 1966 (Fishwick, 1983; and Turner, 1989). All of this has financial implications, directly in the repair and replacement of lost structures and assets, and indirectly through the loss of earnings caused by disruption. In the worst cases human life is lost; for example, the Lynmouth flood of August 15th 1952, when heavy rainfall on the Exmoor uplands flooded the Lyn Rivers, and severely damaged Lynmouth (coastal village). Delderfield (1988) states 34 people were killed or missing, 93 houses or buildings were destroyed or subsequently demolished, 28 bridges were destroyed or badly damaged, and 132 vehicles destroyed. In total this disaster had cost just under £2 million by 1956. Figure 1.1 provides a few illustrated examples of the impact of mountain floods.

Figure 1.1: Example impacts of torrent and mountain stream floods (A) Clearing up after the blockage of the A 591 at Dry Gill (NY 323 152) after the 31st January 1995 floods in the Thirlmere Catchment (English Lake District); (B) Allt Mor torrent in the Cairngorms Scotland, showing boulder deposits and hillslope sediment sources; (C) Fresh debris flow deposits blocking a road in Val Ferret, Switzerland, 21st July 1992 (D) Memorial to the village of Dolgarrog (North Wales) which was destroyed by a flood in November 1925, where 16 people lost their lives.



With regard to natural disasters in Alpine regions, Aulitzky (1974, p24) states- *"Detailed investigations have shown that the increase in natural disasters is not necessarily caused by changes in natural conditions. On the contrary, it is simply that more people are in dangerous areas during critical periods and so there is a much greater chance of catastrophe."* Recent events, have unfortunately shown this to be the case. A flash flood in the Saxeten Bach Gorge (near Interlaken in the Swiss Alps) on 27th July 1999 killed 21 people who were canyoning in the Gorge. A very flashy runoff response followed an afternoon thunderstorm (BBC, 1999). Aulitzky (1974, p v) further suggests that 10,000 torrents endanger the native population and tourists in densely populated Alpine valleys.

In addition to being vulnerable to hazards, humans also influence process activity in upland and mountain environments (Dedkov and Moszherin, 1992; MAFF, 2001), including the operation of torrent systems (Aulitzky, 1974; Wilhem, 1994). Wilhem (1994) suggests that the expansion of winter sports in the Alps has had several detrimental effects. Constructing ski runs destroys the natural vegetation cover and alters the soil structure, thereby increasing surface runoff and soil erosion. Eisbacher and Clague (1984) give the example of deep ravines cut (due to debris flows) below the French ski resort of Les Arcs following snowmelt in March 1981, and consider this a new hazard brought on partly by human activity. In this regard Aulitzky (1974) states that afforestation is the only means of protection against torrent disasters caused by spring snowmelt, as the shadow from trees reduces melt production, and hence flood discharge. Similarly NWSCA (1985) states that New Zealand's forests were removed by European settlers at the end of the 19th Century to make land suitable for farming. The results were considered catastrophic, as the upland soil cover became susceptible to accelerated erosion, with debris being dumped into watercourses, and overland flow on hillslopes resulting in severe flooding.

1.2 Torrent and torrent erosion research in mountainous catchments

Detailed research of torrents and erosion in mountain catchments has largely been undertaken in experimental research basins in the European Alps, specifically in Switzerland, Germany and Italy. Here investigations have focussed on bed material transport and debris flow propagation. Investigations of bedload have sought to establish relationships between bedload yield and runoff (e.g. Billi *et al*, 1995; Hegg and Rickenmann, 1999), and the influence of bed topography and particle size on transport (e.g. Schmidt and Ginz, 1995; Rickenmann, 1997). Debris flow initiation and movement has been monitored by video cameras, ultrasonic and seismic sensors (e.g. Arratano and Marchi, 2000; Massimo, 2000). These techniques allowed the calculation of debris flow front velocity, and demonstrated the potential application for hazard warning. More detailed consideration of these investigations is given in Chapter 2.

Despite this background, very few studies have considered sediment transfer from torrent catchments in a broader sense, i.e. a study of the sediment supply mechanisms and their variations. The studies of Kienholz *et al.* (1991); Schmidt (1994); Billi *et al.* (1995); and Hegg *et al.* (1996) provide the best examples of studies that have considered the role of slope and channel sediment supply mechanisms. However, all but Hegg *et al.* (1996) concentrate on the impacts of individual storm events, hence the understanding of the spatial and temporal changes in sediment delivery to channels over longer time periods is very limited. Therefore there is a need for a more detailed understanding of torrent systems.

In the UK there have been very few investigations of torrent and mountain stream erosion processes. Examples of torrent studies include the study of McEwen and Werritty (1988) in the Allt Mor torrent in the Cairngorms, and Fearnsides and Wilcockson (1928) in regard to Afon Port Llywd above Dolgarrog in north Wales. A larger, though still limited, number of investigations have been undertaken in mountain streams (Carling, 1983; Warburton, 1983; Newson and Leeks, 1985; Carling, 1986; Stott *et al.*, 1986; Carling and Glaister, 1987; Macklin *et al.*, 1992; Carling, 1997; Harvey, 2001). These consider a variety of aspects such as flood impacts, hillslope-channel coupling relationships, bedload yield, and historical channel development. This lack of study is surprising given that 20-30 % of Britain can be described as upland; areas characterised by steep slopes, high rainfall totals and runoff coefficients of 70-90 % (Newson, 1981). Because of this limited research, an opportunity exists to increase knowledge of erosion in UK mountain drainage systems, which is timely given the water resource and hazard aspects outlined in the previous section.

1.3 Research aim and objectives

In the preceding section it has been suggested that in order to better understand torrent erosion, investigations need to consider a broader spectrum of geomorphological processes operating over prolonged periods. It is therefore surprising that in high mountain areas, like the European Alps, torrent research has focussed mainly on sediment yield, and given less attention to slopes or the sediment system as a whole. This thesis considers a range of torrent erosion processes at different spatial and temporal scales in the Cumbrian Mountains (UK). The aim of this thesis is to investigate the nature of torrent erosion in Lake District mountain catchments, under the influence of differing sediment water-flow processes and at a range of spatial and temporal scales. The general objectives of this study are:

1. Quantify process activity in an active torrent over an annual cycle determining sediment supply, transport and storage. This involves constructing a detailed sediment budget.
2. Establish the role of different meteorological events in torrent erosion processes and sediment production rates.
3. Produce longer term estimates of process activity in torrents, to give context for contemporary observations.
4. Consider the frequency and impact of high magnitude sediment-water flow events in torrent catchments.
5. Consider the regional significance of torrents and hillslope debris flows, and determine whether torrents vary in different local areas.

1.4 Study area

The area of investigation for this thesis is the English Lake District, in North West England. To achieve the stated objectives a 'nested-scale' research approach is adopted. The research focuses on two sites in detail, i.e. Iron Crag and Raise Beck. Less detailed, but more numerous and widespread, investigations are then conducted across the Skiddaw and Helvellyn massif regions (see Figure 3.10 for a model of the research approach, and Figure 3.11 for the location of study sites and areas).

Iron Crag is a small (2.4 ha), active torrent system located in the north east corner of the Skiddaw massif, in an area known as the Caldbeck Fells. Research at Iron Crag is primarily related to research objectives one to three. A sediment budget over a twelve-month period enables the quantification of process activity, and allows the different roles of hillslope and channel erosion processes to be determined under different meteorological conditions. Detailed study of the particle size characteristics of sediment collected on the slopes during the monitoring period provides another means of assessing the impact of meteorological events on the processes of hillslope sediment transport. Finally, an analysis of historical aerial photography, sedimentology and chronology of the alluvial fan deposits provides a long-term perspective of the Iron Crag system, allowing the contemporary investigations to be placed in a broader timeframe.

Raise Beck is a larger torrent (133 ha) located south west of Helvellyn, and has a history of high magnitude flood events. These are reconstructed using a combination of documentary records, palaeohydrology and lichenometry. This case study shows the impact of these low frequency events on the torrent system, and the implications of such occurrences on the water resource infrastructure in the area. The study of Raise Beck provides information for research objectives three and four.

The regional study assesses torrents, hillslope debris flows, and to a lesser extent mountain streams in two upland areas: Skiddaw massif (129 km^2) and Helvellyn massif (121 km^2). Morphometric characteristics of torrents in these regions were surveyed and field investigations provided evidence of historical flood events and further information about the frequency of high magnitude flood events. This part of the work addresses research objectives four and five outlined above.

1.5 Thesis Structure

The organisation of the remainder of this thesis is now outlined. Chapter 2 discusses sediment-water flow erosion in upland and mountain catchments; the characteristics of mountain torrents, and main processes operating. The concept of the sediment-water flow spectrum and a morphological continuum form an important section. Torrent erosion research in Europe is briefly outlined providing a framework for several key research questions to be established. The techniques applied to the study of torrent erosion are investigated.

Chapter 3 considers the Lake District National Park, and its environment. The nested-scale research approach adopted by this thesis is described, and this allows the consideration of different process types in areas of contrasting geology. This approach places the detailed case study investigations at Iron Crag and Raise Beck in the broader context of the study region. Characteristics of the study sites and region are given.

Chapter 4 investigates the particle size characteristics of sediment collected by instruments during the sediment budget monitoring period at Iron Crag. A background to particle size analysis, and the process controls on the particle size distribution of sediments are established. Using meteorological data and field observations the dominant process activity during sediment budget measurement intervals are outlined. This allows an investigation of the hypothesised impact of meteorologically driven process activity on the particle size signatures of sediment deposits.

Chapter 5 discusses the application of a sediment budget approach at Iron Crag. This involves continuous monitoring of process activity throughout an entire torrent system. Results include the annual sediment budget model, the temporal variability of system components and the impact of different meteorological events on the dynamics of the system components.

To provide a longer-term context to the contemporary process monitoring of chapters 4 and 5, chapter 6 considers the historical process activity at Iron Crag, with regard to stream channel and fan processes over decadal and millennial timescales. In so doing, the causes of fan aggradation are discussed, and phases of activity are compared to the findings of other British alluvial fan and debris cone chronologies.

Chapter 7 is a study of the Raise Beck torrent in the central Lake District Fells. A review of upland flooding in the UK and the Lake District illustrates the importance of these flood events. Further background to the Raise Beck catchment is given as a precursor to more detailed investigations. These include a reconstruction of the 1995 flood event, and other historical floods for which boulder deposits are preserved in the catchment. Finally, a consideration of the engineering responses to the 1995 flood is presented.

Chapter 8 provides a regional assessment of sediment-water flow activity in the Lake District, specifically on the Skiddaw and Helvellyn massifs. This determines the significance of both torrents and debris flows in the landscape, whilst also discussing the preferred siting characteristics of these landforms. An assessment of the magnitude and frequency characteristics of torrents and debris flows concludes this chapter. These investigations provide the broader context for the case studies at Iron Crag and Raise Beck.

Finally, Chapter 9 summarises and concludes the investigations undertaken during this thesis. A synthesis of the main findings are outlined and these are then considered in respect to the concept of landscape sensitivity. A preliminary consideration of the likely impacts of land use and climate changes on upland and torrent erosion is given. Under such conditions, torrent and mountain stream erosion processes may become more important landscape features in the future. Finally, limitations identified during the research are presented, along with ideas for further investigations with regard to torrent erosion processes.

CHAPTER 2: SEDIMENT-WATER FLOWS AND EROSION IN UPLAND/ MOUNTAIN CATCHMENTS: BACKGROUND AND METHODS OF STUDY

2.0 Scope of chapter

This chapter provides a review of erosion processes in upland and mountain catchments. Section 2.1 discusses the characteristics of uplands and mountains and the diagnostic criteria are used to define such environments in the UK and Lake District. Section 2.2 identifies the geomorphological process types in mountains, followed by a comparison of the rates of process activity occurring in UK and other mountain environments, with regard to surface processes and sediment yield (suspended and bed load).

Section 2.3 discusses sediment-water flows, and introduces the concept of a morphological continuum of process-forms that reflect the variety of sediment-water flow processes active in mountain environments. Torrents are the central member of this continuum providing a strong linkage between hillslope and channel units. Research investigations into torrent erosion processes are currently dominated by investigations of bedload material transport and channelised debris flows. It is demonstrated that a more comprehensive understanding of the torrent system is required.

Section 2.4 considers the basis of two techniques used for the study of torrents and torrent erosion in the English Lake District, namely sediment budgeting and palaeohydrology. Sediment budgets provide a measurement framework and allow spatial and temporal changes, as well as hillslope- channel interactions to be determined. Palaeohydrology allows high magnitude-low frequency events to be investigated using evidence from preserved flood deposits. Once deposits are dated this gives a context for short term detailed sediment budget studies. Finally, section 2.5 summarises the chapter and indicates its linkage with other parts of the thesis.

2.1 Definition of mountains and uplands in the UK and Lake District

It is widely acknowledged that providing a common definition of a mountain or upland area continues to be an elusive goal (for example, Peattie, 1936; Price, 1981; Gerrard, 1990; Barry, 1992; Debarbieux, 1999; Messerli, 1999; Beniston, 2000). Gerrard (1990) states that this situation develops because mountains are diverse landforms, and the use of a single discriminatory criterion such as summit altitude is insufficient. Price (1981) and Gerrard (1990) illustrate this point by stating that the high plateau of Tibet (5000 m asl.) is not considered as mountainous, yet elevations as low as 100 m asl. in North America are. Despite this criticism Milliman and Syvitski (1992) classify river basins around the world according to maximum altitude. It is suggested that high mountains have headwaters in excess of 3000 m; mountains 1000-3000 m; uplands 500-1000 m; and lowlands 100-500 m. A more objective topographic measure is that of relative elevation (Price, 1981; Barsch and Caine, 1984; Gerrard, 1990), which is the altitudinal difference between highest and lowest points in an area (Price, 1981). However, like summit altitude this is subject to local interpretation. Price (1981) states that in Europe a minimum range of 900 m has been used, whilst ranges as low as 300 m have been applied in the United States. Gerrard (1990) continues that the horizontal distances between ridges and valley are important as this controls the gradient of the elevation change. Despite the prevailing problem a number of definitions are given, and these can be applied in a UK context.

Barsch and Caine (1984) state that most definitions of mountains will include characteristics important for the description of processes acting upon them. These being: high top altitude, steep gradient, rocky terrain, and presence of snow and ice. Additionally, characteristics controlled by altitude, relative elevation and topography provide the basis for alternative identification of mountain terrain. In this respect Troll (1972, 1973) indicates climatic vegetative belts to be diagnostic; a high mountain system is that existing above the timberline, whereas a mountain system has more than one vegetation belt but fails to achieve alpine elevation. Similarly Becker and Bugmann (1997) consider the characteristics relating to these sharp gradients to be diagnostic: rapid and systematic changes in temperature and precipitation over very short distances; sharp climatic changes independent of daylight hours; enhanced runoff and erosion; and systematic changes in other environmental properties such as soil depth, CO_2 and UV-B with elevation.

Price (1981); and Goudie (1990) give two definitions of mountains encompassing a similar range of diagnostic characteristics:

"an elevated landform of high local relief e.g. 300 m (1000 ft), with much of its surface in steep slopes, usually displaying distinct variations in climate and associated biological phenomena from its base to its summit." (Price, 1981, p 5)

"substantial elevations of the earth's crust above sea level, which result in localised disruptions of climate, drainage, soils, plants and animals..." (Goudie, 1990, p 344)

In the UK a variety of adjectives are used in the naming of non-lowland areas, including uplands, mountains, highlands, moors, fells, hills etc (e.g. Moggridge, 1983). Ratcliffe (1990) considers uplands to be a general category covering all these terms. A range of basal altitudes are given for British uplands, i.e. 300 m O.D. (Atherden, 1992) and 400 m O.D. (Ballantyne and Harris, 1994). In this context about one third of the UK is considered to be upland (Atherden, 1992; DoE, 1995b; Fielding and Haworth, 1999) (Figure 2.1). Alternatively, Ratcliffe (1977) defines uplands typically above enclosed farmland. Fielding and Haworth (1999) (Figure 2.2) consider this to be an altitudinal boundary that is a surrogate for climate and its implications on plant growth. It should however be noted that Troll's (1972, 1973) classification is inapplicable to the UK, as many uplands are above the actual treeline, which is as much a product of land management as it is climate. The general characteristics of these areas include: resistant rocks forming blocks of higher ground; steeper gradient; severe climate and less fertile soils (Atherden, 1992; Ballantyne and Harris, 1994).

Having presented definitions of both mountains (in general) and UK uplands it becomes relevant that the difference between the two is made clear and their application in the UK specified. Barsch and Caine (1984) provide altitude-based criteria for the division of different types of mountain system. Table 2.1 indicates the divisions employed with further modifications. The re-labeling of 'mountainous

Figure 2.1: Upland and lowland Britain, differentiated in terms of altitude, where upland areas are above 400 m O.D. (From Ballantyne and Harris, 1994)

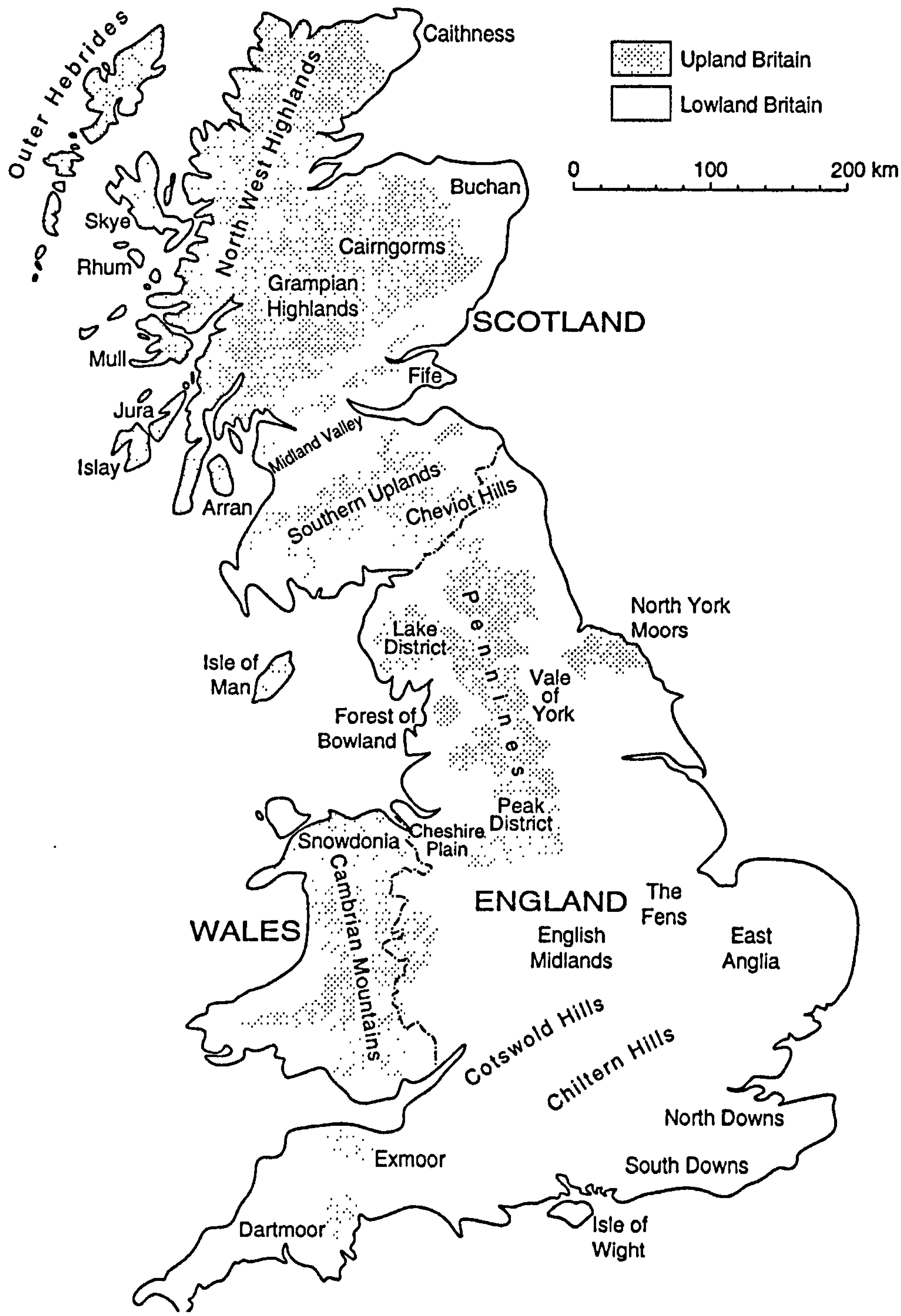
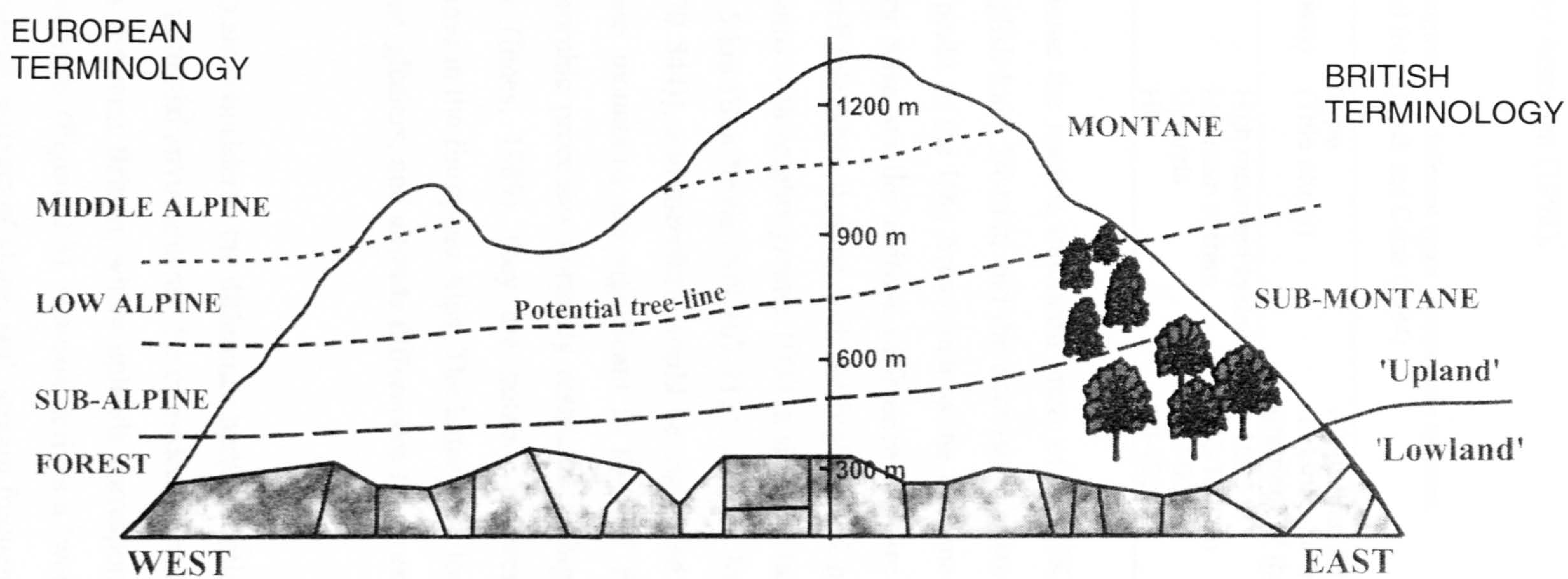


Figure 2.2: Zonation of upland/ mountain habitat within Britain and Ireland
(From Fielding and Haworth, 1999)



terrain' as uplands allows a division between the UK's upland and mountain landscape units. The inclusion of uplands is valid as it matches the altitude difference of known upland areas such as the Pennines, and further corresponds to the 300 m plus elevation cited by Atherden (1992).

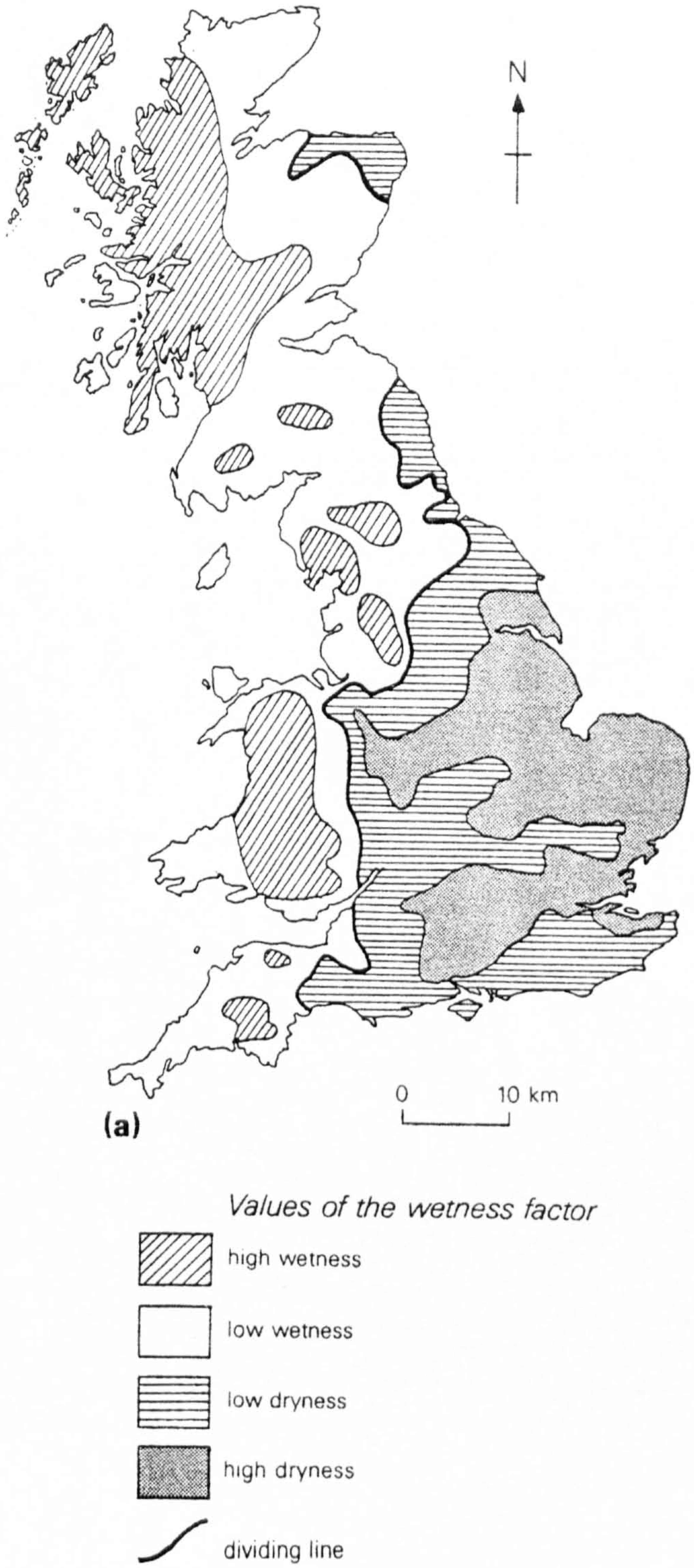
Table 2.1: Relief contrasts in different types of mountain systems. Adapted from Barsch and Caine (1984)

Type (Barsch and Caine, 1984)	Type (This study)	Altitudinal difference (over 5km distance, to incorporate the gradient of the elevation change)
High mountain system	High mountain system	> 1000 m
Mountain system	Mountain system	500-1000 m
Mountainous terrain	Uplands	100-500 m
Hilly terrain	Hills	50-100 m

Using this basic scheme the notable mountain areas of the UK are Snowdonia in North Wales, the English Lake District, and the Scottish Highlands, as these are the areas of the highest peaks in the UK. Areas such as the Pennine chain, North York Moors, and Dartmoor have smaller altitude difference and are therefore uplands. This scheme is less reliable when dealing with the highest UK peaks. For example, some Scottish mountains with heights greater 1000 m show altitudinal differences in excess of 1000 m in 5 km [Ben Nevis (NN 167 712); Aonach Moor (NN 193 730); An Teallach (NH 070 844)], and therefore would be classified as 'high mountain systems'. Whilst these mountains are significant in the UK for having climatic conditions and geomorphic processes normally restricted to higher altitude arctic-alpine environments (Innes, 1989), they are notably different from true high mountains such as those in the European Alps. The latter have local features such as permanent snow cover, glaciers, and altitude differences far in excess of the 1000 m threshold.

Newson (1978, 1981) also considered the difference between uplands and mountains in the UK in relation to fluvial environments. He considers mountain terrain to occur only locally in north and west Britain, where uplands correspond to wet areas and mountains to very wet areas (Figure 2.3). Newson derives a 'wetness factor' (based on a principal components analysis of slope, soil, stream frequency, and net rainfall values in 410 catchments (NERC, 1975; Newson, 1978)) to describe mountain geomorphological processes. This suggests that such processes are widespread and

Figure 2.3: The derivation of upland and lowland areas in the UK using a wetness factor derived from catchment characteristics. (Adapted from Newson, 1981)



occur in areas normally considered to be uplands, e.g. the Pennines (Figure 2.3).

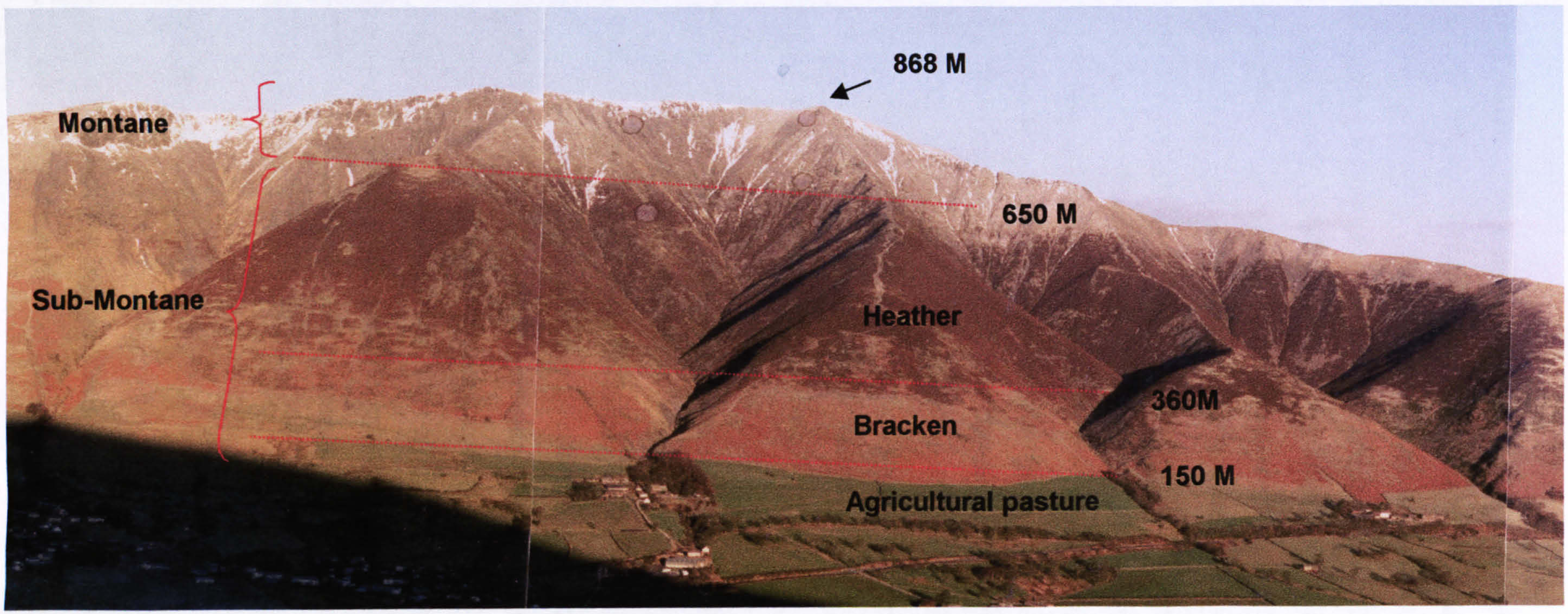
Newson (1981) explains the existence of mountainous process beyond mountains to be a function of climate (steep lapse rates, high rainfall totals, low temperatures) and geomorphic conditions (paraglacial sediment supply). In summary, the UK has a mix of uplands and low mountains, though the exact definition depends on whether an altitudinal or multivariate catchment classification is applied. Here the Barsch and Caine (1984) approach is considered most applicable, as it defines mountains on a global scale and not just in a UK context, although it is acknowledged that climatic conditions (Taylor, 1976; Newson, 1981; Innes, 1989) and sediment supply legacies (Newson, 1981) result in mountain-type processes at lower altitudes.

The Lake District Fells can therefore be classified as a central mountain area with lower surrounding uplands. Ordnance Survey maps (Landranger sheets 89 and 90) identify the Lake District Fells as the 'Cumbrian Mountains'. Table 2.2 demonstrates that an altitude difference approach (Barsch and Caine, 1984) applied to the highest fells of the central district, shows 31 of the 32 fells listed to be mountains. Another characteristic indicative of mountain status in the Lake District is the zonation of upland habits with altitude (Pearsall and Pennington, 1973; Ratcliffe and Halliday, 1997) e.g. sub-montane (heath and grassland) and montane (dwarf shrub, moss-heath, grassland) (Fielding and Haworth, 1999). Atherden (1992) states that the potential tree line altitude in England and Wales is about 600 m, marking the transition between the two types of upland habitat (Figure 2.2). An example of these habitat changes in the Lake District is illustrated by Figure 2.4. This view of the south face of Blencathra shows different habitats from managed agricultural pasture (150-250 m O.D.), to bracken (250 m O.D. -360 m O.D.), to heather dominated heath (360 m O.D. to c.650 m O.D.), and, above 650 m O.D., montane habitats.

Table 2.2: The application of Barsch and Caine (1984) criteria (altitudinal difference) for the classification of Lake District Fells. (M= Mountain [500-1000 m], U= Uplands [100-500 m])

Area of Lake District	Fells	Top altitude (m O.D.)	Basal altitude in 5 km radius	Altitude difference	Mountain system category
Skiddaw Massif	Skiddaw	931	75	856	M
	Blencathra	868	150	718	M
	Carrock Fell	660	160	500	M
	Knott	710	200	510	M
Helvellyn Massif	Great Dodd	857	140	717	M
	Raise	883	145	738	M
	Helvellyn	950	145	805	M
	Fairfield	873	80	793	M
	Hart Crag	822	80	742	M
	St. Sunday Crag	841	145	696	M
Eastern Fells	High Street	828	150	678	M
	Ill Bell	757	130	627	M
	Stony Cove Pike	763	140	623	M
	High Raise	802	150	652	M
	Place Fell	657	160	497	U
Coniston Fells	Coniston Old Man	803	45	758	M
	Wetherlam	762	50	712	M
Scafell area	Scafell Pike	978	65	913	M
	Scafell	964	65	899	M
	Great End	910	65	845	M
	Great Gable	899	65	834	M
	Pillar	892	70	822	M
Langdale area	Bowfell	902	90	812	M
	Crinkle Crags	859	90	769	M
	Harrison Stickle	736	60	676	M
	High Raise	762	85	677	M
	Ullscarf	726	83	643	M
	Glaramara	783	90	693	M
Buttermere and north west	High Stile	807	100	707	M
	Dale Head	753	80	673	M
	Grasmoor	852	85	767	M
	Grisedale Pike	791	70	721	M

Figure 2.4: Altitudinal variation in the habitats on the southern face of Blencathra, indicating dominant vegetation cover. (Photograph taken from Threlkeld Knotts, NY 330 230)



2.2 Process types and rates

Geomorphological investigation of process and interaction with materials and forms developed rapidly in the 1950s and 1960s (Derbyshire *et al.*, 1979; Gregory, 1985; Summerfield, 1994, Gregory, 2000). This followed the realisation that historical approaches, which largely concentrated on landforms alone, had reached their limit and in any case process was already being considered by related disciplines such as glaciology and hydrology (Gregory, 1985). Indeed Strahler (1952) considered the absence of process knowledge in geomorphology as a weakness which had to be addressed to establish geomorphology as a research science. Gregory (1985) comments that this drive for process understanding caused some fragmentation in geomorphology, as branches became more associated with related disciplines. Hence geomorphological textbooks (for example, Brunsden and Doornkamp, 1973; Twidale, 1976; Bloom, 1978; Embleton *et al.*, 1978; Derbyshire *et al.*, 1979; Chorley *et al.*, 1984; Cooke and Doornkamp, 1990; Goudie, 1990; Trenhaile, 1990; Summerfield, 1994) segregate earth surface studies into a number of general process groups that are responsible for the denudation of landforms, i.e. weathering, hillslope, fluvial, coastal, glacial, periglacial, and aeolian.

Mountains and uplands show evidence of most of the process activity listed above (Rapp, 1960; Price, 1981; Zimmermann *et al.*, 1986; Gardner, 1989; Gerrard, 1990; Ballantyne, 1991a; Navarro *et al.*, 1994; Evans, 1997a) and Barsch and Caine (1984) state that few of the processes found in mountains are exclusive to this environment. Following Caine (1974), Barsch and Caine (1984) consider a four way classification of process systems in high mountains: namely glacial, coarse debris, fine sediment, and geochemical. However, this process cascade is not of uniform applicability; for example in the UK no current glacial process activity exists, though it is a landscape that was once subject to glacial activity and continues to adjust to its impact (Newson, 1981, Ballantyne, 1991a).

2.2.1 UK mountain processes

Ballantyne and Harris (1994) state that both mountain and upland parts of the UK still show evidence of active maritime *periglaciation* though at rates lower than those occurring in the arctic-alpine conditions of the Late Devensian. In illustration of this Boardman (1992) states that periglaciation in the Lake District had a substantial effect on the landscape, especially during periods of restricted glaciation, creating thick deposits of frost- shattered debris. These debris sheets are now vegetated, and have well-developed soil profiles, suggesting little addition of frost shattered debris under the temperate conditions of the last 10,000 years. With regard to contemporary periglacial features both Ballantyne (1991a) and Ballantyne and Harris (1994) consider three forms of freeze-thaw: rock breakdown, frost-sorted patterned ground, and solifluction. Numerous studies have identified patterned ground features in the Lake District (Hollingworth, 1934; Hay, 1936, 1943; Caine, 1963a, 1972; Warburton, 1985, 1987, 1997; Boardman, 1996; Warburton and Caine, 1999) including small sorted stripes, nets and isolated stone circles. Warburton and Caine (1999), on the basis of continued monitoring, show that stripes at High Pike (NY 318 350) have remained active since Hollingworth's identification of these features in 1934. Warburton (1998, *pers. comm.*) has also identified active solifluction lobes on the fells of the Skiddaw massif in the Lake District.

Ballantyne and Harris (1994) consider *wind* responsible for deflation surfaces, patterned ground and turf bank terraces. However, with the exception of Hollingworth (1934) who considered turf bank terraces, no other research on the effects of wind erosion have been conducted in the Lake District. In the nearby North Pennines Warburton (2000) considers wind to be an active process in the continued erosion of a peat deflation surface. Monitoring has shown wind-driven peat transport to be far more significant than surface wash processes. Further work is required to establish the significance of aeolian erosion in the UK uplands.

With regard to *hillslope processes*, HMSO (1994) indicates that rockfalls, landslides, and debris flows occur in the UK. Rockfalls provide a source of debris for talus slope accumulation. In Lake District, Andrews (1961) states that the Wasdale Screes (NY 155 045) are active, but that large areas are in a 'retarded state of development', being more active in the past. Caine (1963b) also shows low angle screes at five sites around Grasmoor (NY 175 205) to be active, with measured surface movements of between 0.15- 0.2 m in one winter. HMSO (1994) demonstrate that mass movements are widespread throughout the UK, and record 8365 cases in 1991. Of these only 3621 had a known failure mechanism, of which 52 % were slides. Only 11 rotational slides are identified in Cumbria, which is considerably less than the occurrence in the Pennine counties of Derbyshire (232), North Yorkshire (42), West Yorkshire (19). Active mass movements in upland areas are fairly uncommon. A notable exception in an upland area is the Mam Tor landslide in north Derbyshire (SK 128 836) which is investigated by Skempton *et al.* (1989), who state that the toe is moving at a rate of 7 m 100 a^{-1}. By its own admission HMSO (1994) probably underestimates the number of landslide failures in the UK; indeed personal observation has identified deep seated landslides in the Lake District not depicted on geological maps. Further to this, many shallow failures occur on hillslopes which go unrecorded. Debris flow features have been investigated most extensively in the Scottish Highlands (Innes, 1982, 1983a, 1989; Jenkins *et al.*, 1988; Luckman, 1992), but also in parts of Wales (Addison, 1987 - Snowdonia; Statham, 1976 - Black Mountain); and the Howgill Fells (Harvey, 2001). There is no published account of contemporary debris flow activity in the Lake District. In addition to these mass movements, other types of hillslope activity occur in upland areas. These include slow mass movement (creep) and surface wash. Saunders and Young (1983) outline the results of studies of both processes in the UK uplands. Table 2.3 shows that soil creep has been studied in Weardale (Anderson, 1977; Anderson and Cox, 1978) and Derbyshire (Young, 1978) where rates of up to 2.4 mm a^{-1} are reported. Surface wash has been studied in Wales (Day, 1977); Yorkshire (Imeson, 1974); and the Peak District (Evans, 1974) and rates of ground lowering are as high as 2285 $m^3\ km^{-2}\ a^{-1}$.

Table 2.3: Comparative rates of creep and surface wash in the UK uplands (adapted from Saunders and Young, 1983).

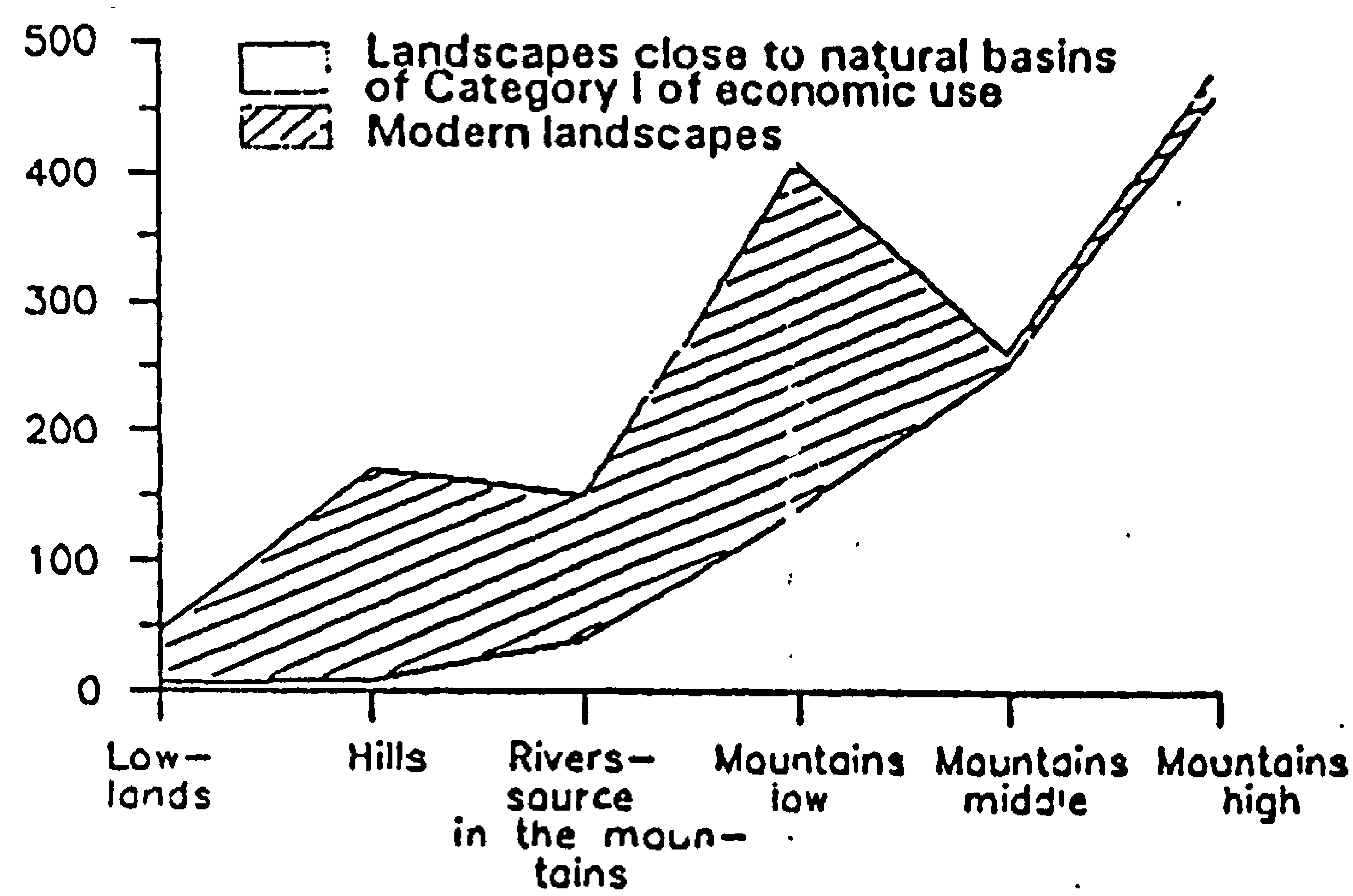
Process	Author	Location	Maximum process rate (mm a^{-1} / $m^3\ km^{-2}\ a^{-1}$)
Creep	Anderson and Cox (1978)	North Pennines UK	2.2
	Anderson (1977)	North Pennines UK	2.4
	Young (1978)	Peak District UK	0.25
Surface Wash	Day (1977)	Wales	*0.4- 0.6*
	Imeson (1974)	Yorkshire	*0-10,000*
	Evans (1974)	Peak District, UK	*34- 2285*

Studies of *fluvial* and hydrological processes have dominated British geomorphological research (Young, 1978; Newson, 1979). Gregory (1978) indicates that in 1975, 27.7% of research could be classified as fluvial. More recently Gregory (2000) shows that the dominance of fluvial geomorphology continues, the 1996 RAE (Research Assessment Exercise) examined more than 1700 publications between 1992 and 1996, and showed 19.7% were water related. Studies in upland areas have included the impact of flooding (Carling, 1986; Harvey, 1986; Carling and Glaister, 1987; McEwen and Werritty, 1988; Carling, 1997); channel pattern change (Milne, 1982; Warburton and Danks, 1998); sediment transport/ yield (Carling 1983; Richards and McCaig, 1985; Newson and Leeks, 1985; Stott *et al.*, 1986; Ashworth and Fergurson, 1989; Warburton and Demir, 1998; Warburton and Evans, 1998; Demir, 2000), and fluvial chronologies (Macklin *et al.*, 1992; Rumsby and Macklin, 1994; Tipping, 1994; Merrett and Macklin, 1998). Of these studies only a small number were conducted in the Lake District, including the flood reconstructions by Carling and Glaister (1987) and Carling (1997); and the bedload sediment yield monitoring reported by Newson and Leeks (1985).

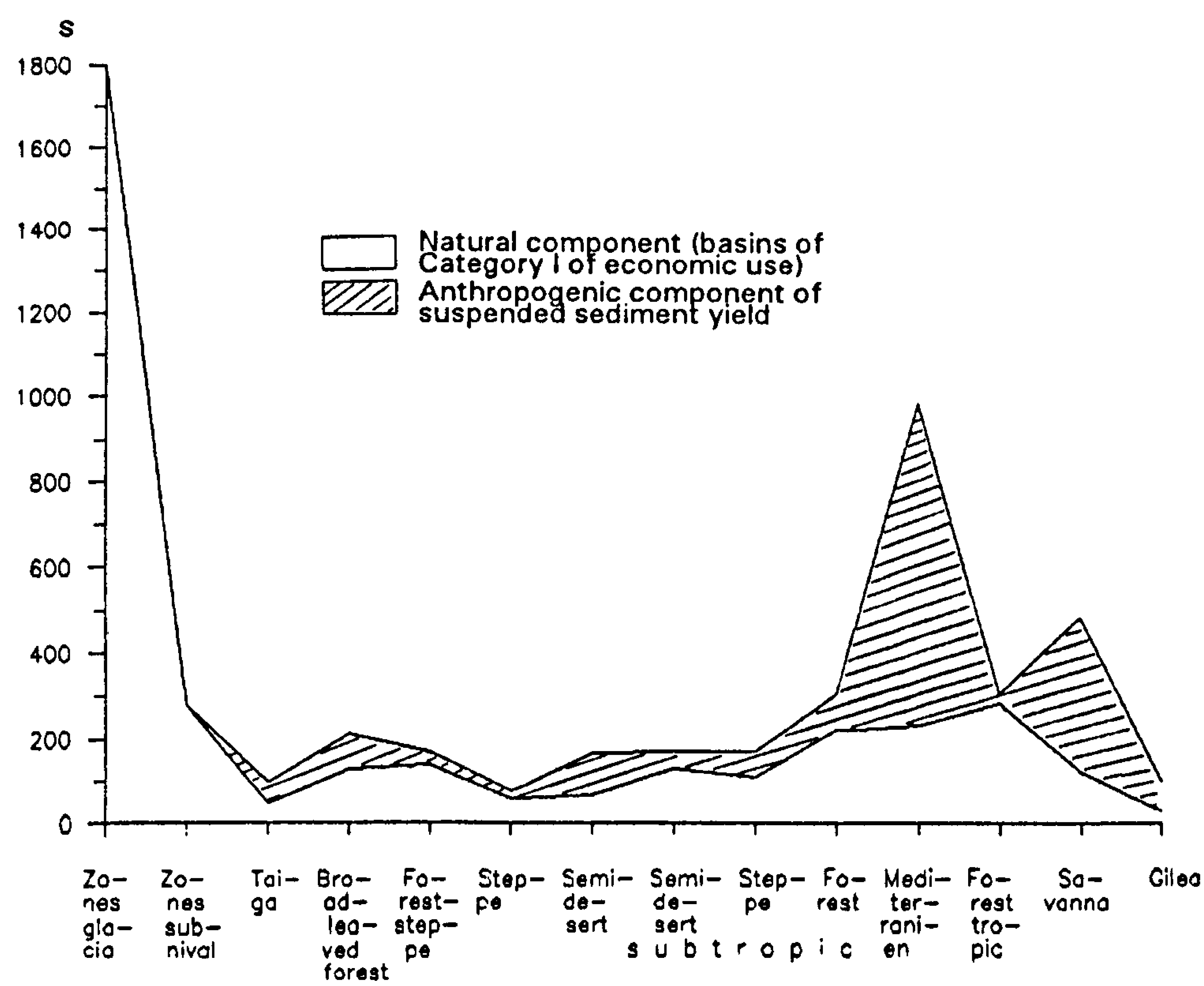
The foregoing review provides an indication of processes operating in the UK uplands and mountains, but on the whole omits to indicate process rates, and how these compare with process activity in other parts of the world. It is widely accepted that rates of geomorphic processes are greater in upland areas, and intensify with increasing altitude and relative elevation (Ruxton and McDougall, 1967; Carson and Kirkby, 1972; Caine, 1974; Newson 1979; Price, 1981; Barsch and Caine, 1984; Gerrard, 1990). Young (1969), using evidence of river load, reservoir sedimentation, surface process measurements, and geological evidence, shows greater rates of ground loss in areas of steeper relief. Similarly Dedkov and Moszherin (1992) using a collection of sediment yield data for 3700 river basins around the world show that erosion in natural mountain areas is 27 times greater than in lower areas. Process rates generally increase with increasing altitude between hills and high mountains, and the highest rates of suspended sediment yield originate from glaciated zones which are unvegetated and have high runoff (Figure 2.5). Also, Milliman and Syvitski (1992) consider sediment load and yield in 280 rivers, and show sediment discharge from mountain rivers to be greater than upland rivers and in turn greater

Figure 2.5: Variation in suspended sediment yield (t km^{-2} a^{-1}) according to relief (A); and in different landscape zones/ belts of mountain regions (B). Where category 1 economic use refers to a low degree of human interference on a natural landscape, i.e. less than 30 % land cultivation and up to 70 % vegetation cover (From Dedkov and Moszherin, 1992).

(A)



(B)



than lowland rivers. Given the UK has no active glaciation and is of a lower elevation, process activity is expected to be less. Comparisons of sub-aerial process rates and suspended/ bedload yield data in both UK and other environments are needed to test this hypothesis.

Caine (1976) compares contemporary sediment movement in sub-aerial situations by estimating energy conditions (work and power). This approach provides a common unit of measurement that allows comparison of the relative significance of different processes (Caine, 1976, Warburton, 1993). A compilation of published data (Table 2.4) compares geomorphological process activity on An Teallach (north west Scotland) with higher mountains elsewhere. Ballantyne and Harris (1994) state that process activity at An Teallach is as effective as that occurring in other mountain areas which experience more severe climatic conditions (Karkevagge and San Juan). The reasons for this are: the greater effectiveness of rapid mass transport processes; the effectiveness of aeolian transport, which should be considered in the light of a ready supply of entrainable material; and the importance of solute transport. These process rates are the same order of magnitude as, and sometimes exceeding, those in the higher mountains areas. However, An Teallach is likely to have process rates greater than those experienced by most British mountains given its height (1062 m O.D.), high precipitation (3600 mm a^{-1} at 670m O.D.), and strong winds (Ballantyne, 1987, 1991a; Ballantyne and Harris, 1994). To give this more context an original table of Caine (1976, Table 2) includes process rates from other mountain areas, including the English Lake District and the Canadian/ American Rockies (reported in Table 2.4). The rates of mudflow activity reported by Curry (1960), i.e. 33.414 W km^{-2}, in central Colorado show An Teallach to be insignificant in regard of slide/ flow mass movement activity. The surface wash rates reported by Caine (1963a), i.e. 0.002 W km^{-2}, show the Lake District to have lower rates of activity than the San Juan Mountains and Canada (Mackay and Mathews, 1974). Solute transport at An Teallach is similar or less than that in the American and Canadian Rockies (Hembree and Rainwater, 1961; and, McPherson, 1971). Therefore the statements by Ballantyne (1987, 1991a) and Ballantyne and Harris (1994) that An Teallach is of similar status to higher mountains is not completely correct. Also by their own admission there remains a need for more data to substantiate the relative importance of different forms of mass movement activity on a wider basis.

Table 2.4: Comparative rates of process activity in different mountain environments, expressed in watts per square kilometre per annum.

Process set	**An Teallach UK (Ballantyne, 1991)**	**Karkevagge North Sweden (Rapp, 1960)**	**San Juan Mountains (Caine, 1976)**	**Other studies reported by Caine (1976)**
Rockfall	1.689	0.405	0.133	0.102 (Gardner, 1970)
Avalanches	slight	0.453	0.001	-
Landslides and debris flows	0.560	1.997	0.362	33.414 (Curry, 1966)
Creep and solifluction	0.175	0.166	0.109	-
Surface wash	slight	slight	0.147	0.002 (Caine, 1963) 0.190 (Mackay & Mathews , 1974)
Wind action	0.394	-	-	-
Solute transport	9.017	2.828	0.104	4.040-7.614 (Hembree & Rainwater, 1961) 20.104 (McPherson, 1971)

In this regard Warburton (1993) expresses geomorphological process activity in terms of work for the Bas Glacier d'Arolla proglacial zone. Unfortunately these data are not expressed in the same format as those in Table 2.4, i.e. not in W km^{-2} a^{-1}, but instead with regard of the actual length of time and area over which process activity is monitored. Comparison of process rates from these studies whilst useful, is nevertheless flawed by the small number of studies.

An assessment of published mountain and upland sediment yield data (both suspended load and bedload) provides a basis for a comparison of UK and other environments. Table 2.5 summarises suspended load data. This shows that UK rivers and streams are noticeably less active than rivers in other countries. The mean UK suspended load is 67 t km^{-2} a^{-1}, whereas for the rest of the world the mean is 1641 t km^{-2} a^{-1}, some one and a bit orders of magnitude greater. The highest recorded UK suspended sediment load of 463 t km^{-2} a^{-1} (Johnson 1988, 1993) is an exception to the UK average. Table 2.6 provides a comparison of bedload yields, and once more shows the relative inactivity of British mountain environments. The mean value of UK bedload yield 39 t km^{-2} a^{-1}, is similarly near to two orders of magnitude less than the rest of the world mean value (2219 t km^{-2} a^{-1}). The highest UK value of 144 t km^{-2} a^{-1} (Newson and Leeks, 1985) is exceeded in all but one of the non-UK locations. These findings support the statements of Dedkov and Moszherin (1992), and Milliman and Syvitski (1992) that sediment yield is positively related to altitude. However, it has to be borne in mind that these comparisons of sediment yields in mountain catchments are based on small selections of data, which influence the mean yields. Furthermore, it should be remembered that some of the non-UK data are for glaciated catchments, and are therefore immediately different to UK drainage basins.

Table 2.5: A comparison of a selection of suspended sediment yields from the UK and other mountain and upland locations

Country	Location	Author	Suspended sediment ($t\ km^{-2}\ a^{-1}$)
UK	Southern Uplands	Robinson and Blyth (1982)	3-25
UK	North York Moors	Soutar (1989)	0.5-1.5
UK	Plynlimon, Mid Wales	Moore and Newson (1986) Leeks and Roberts (1987) Leeks (1992)	6.1-12.1 35.2 24.4- 57.1
UK	Balquhidder, Scotland	Stott *et al.* (1986); and Johnson (1988, 1993)	39.2-462.8
UK	Loch Ard	Ferguson *et al.* (1991)	55.2-98.4
UK	Pennines	Labadz (1988)	55
UK	North Pennines	Crisp (1966)	112
UK	Wales	Lewin (1977)	0.93- 255
UK	North Pennines	Carling (1983)	12.1- 24.7
Columbia	Andes: Rio San Juan Rio Patia	Restrepo and Kjerfve (2000)	 1150 972
New Zealand	Hawkes Bay, North Island (coastal hills)	Fahey and Marden (2000)	6.4- 65
New Zealand	Rakumara Ranges, Waipaoa River	Trustrum *et al.* (1999)	6750
New Zealand	Western Southern Alps	Griffiths (1979)	170-13,300
Canada	Canadian Rockies	McPherson (1971); Nanson (1974)	>1000
Canada	Canadian Rockies	Slaymaker (1972)	6.4- 1333
Canada	Canadian Rockies	Hammer and Smith (1983)	245-361
USA	North central California	Lehre (1982)	607
Norway	Engabreen Nigardbreen	Kjeldsen and Ostrem (1980)	244-310 183-283
Switzerland	Alps, Valais	Beecroft (1983)	349
Switzerland	Alps, Valais	Beecroft (1987)	1812- 1979
Switzerland	Alps- Valais: Bas Arolla Tsidjiore Nouve Haut Arolla	Warburton (1989)	 1397-3601 1788 3095

Table 2.6: A comparison of a selection of bedload sediment yields from the UK and other mountain catchments.

Country	Location	Author	Bedload ($t\ km^{-2}\ a^{-1}$)
UK	Plynlimon, Mid Wales	Moore and Newson (1986) Leeks (1992)	6.4- 38.4 11.8
UK	Lake Vyrnwy, Mid Wales	Newson (1980)	113
UK	Balquidder, Scotland	Stott *et al* (1986)	0.05- 1.7
UK	Lake District	Newson and Leeks (1985)	29-77 103-144
UK	Ben Nevis, Scotland	Richards and McCaig (1985)	26
UK	Wales	Lewin (1977)	3.7
UK	North Pennines	Carling (1983)	0.3-0.6
UK	North Pennines:	Warburton and Evans (1998)	58 4.9
Norway	Engabreen Nigarsbreen	Kjeldsen and Ostrem (1980)	146-172 80-215
Canada	Canadian Rockies	Hammer and Smith (1983)	350-438
Switzerland	Alps- Valais	Beecroft (1983)	800
Switzerland	Alps- Valais	Beecroft (1987)	895- 9666
Switzerland	Alps- Valais: Bas Arolla Tsidjiore Nouve Haut Arolla	Warburton (1989)	 4431-6158 4093 1397

2.3 Sediment-water flows and torrents

The focus of this research is erosion caused by sediment-water flow processes in mountain drainage basins, specifically torrents. In this regard several important aspects are now considered: firstly, the process continuum of sediment-water flows; secondly, morphological continuum of drainage basin features, of which torrents are a member that incorporate both fluvial and hillslope erosion processes. Finally, torrent erosion research in UK and elsewhere is reviewed as a basis for the research conducted in this study.

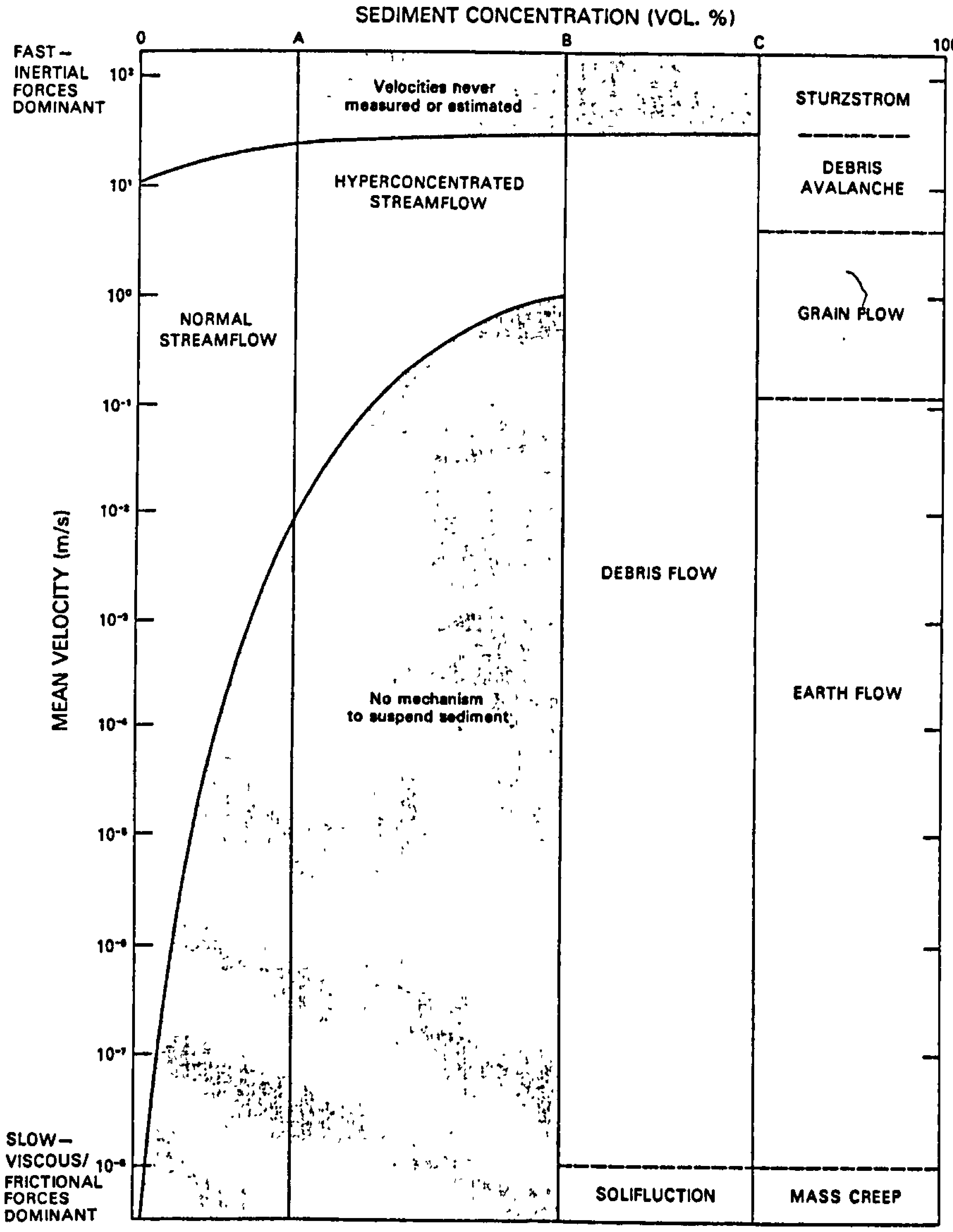
2.3.1 The sediment-water flow spectrum

Pierson and Costa (1987) state 'when a physical substance is subjected to an applied stress (e.g. gravity) of sufficient magnitude, deformation will occur'. If the deformation is irreversible it is a flow. Pierson and Costa (1987) continue; 'the material subject to the stress is usually a mixture of particulate solids (rock, soil, organic debris), water, and air'. Costa (1988, p113) states "*when investigating floods, especially in small, mountainous basins, one of the most important tasks is to properly identify the flow process that occurred in the basin.*" Failure to identify flow types results in scientific misunderstanding and erroneous remedial practices (Costa, 1988). The different flow processes are a function of the different mixtures of solids, water and air. Pierson and Costa (1987), Costa (1988), and, Coussot and Meunier (1996) recognise a spectrum of sediment-water flows that result from different mixtures. On the basis of rheological, geomorphic and sedimentological evidence sediment-water flow types can be categorised.

Pierson and Costa (1987) argue that the rheology (the study of materials in a fluid state) of a sediment-water mixture can be approximated from the velocity of sustained flow on slopes or in channels. Identified flow processes move at characteristic rates, which can be measured in the field (this is, of course, subject to being able to make such measurements). The rheological response of a sediment-water mixture at a given velocity is governed primarily by the sediment concentration and is affected to a lesser extent by the sediment composition (frequency of sizes of sediment), and the physical and chemical properties of the particles. The most sensitive parameter is the sediment concentration. It is assumed that the physical and chemical properties of particles are less variable than sediment concentration in a particular area and are therefore taken to be of secondary importance.

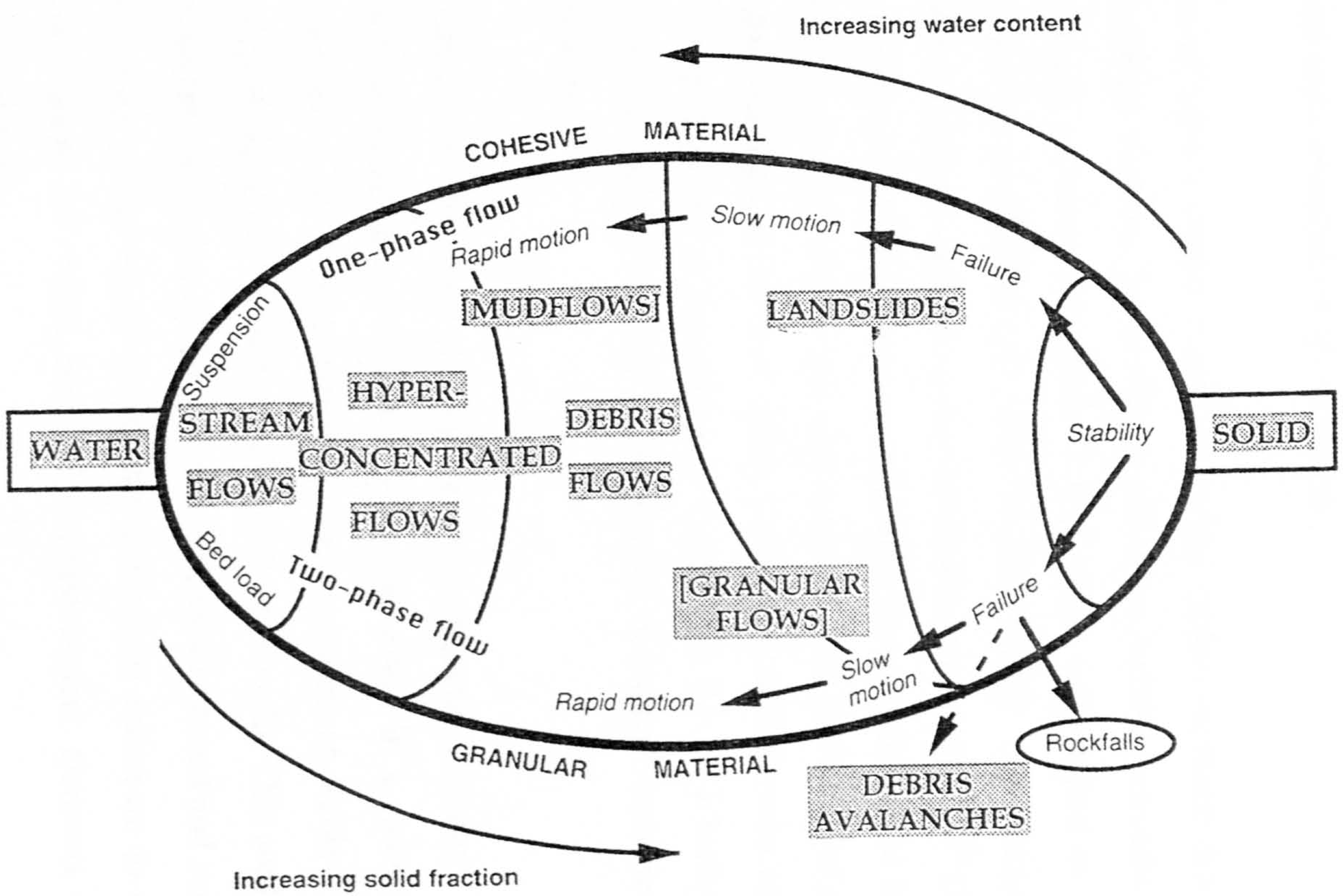
Using these arguments Pierson and Costa (1987) classify sub-aerial sediment-water flows. They construct a two-dimensional matrix in which flows are located according to deformation rate (mean velocity) and sediment concentration, with the composition of the mixture held constant as a coarse, poorly sorted, non-cohesive hillslope colluvium. Using this scheme three rheological thresholds are established (Figure 2.6). Threshold 'A' separates normal streamflow (Newtonian fluid) and hyperconcentrated streamflow (non-Newtonian fluid). Threshold 'B' separates hyperconcentrated flows from slurry flows. Threshold 'C' separates slurry flow from granular flow. If the composition of a mixture were introduced as a third controlling variable a more complex model would result, by shifting the position of thresholds. Whilst this would more closely represent reality, it would be more difficult to apply. Pierson and Costa (1987) use an imprecise scale for the x-axis, locating the thresholds according to the fixed sediment composition. They do, however, indicate which way the thresholds would shift for changes in the sediment composition. More cohesive sediment (finer) would shift the thresholds to the left. For coarser, better sorted, non-cohesive sediment there is a shift to the right. Pierson and Costa (1987) correlate their conceptual diagram with geomorphological process terms (Figure 2.6), for example debris flows have high sediment concentrations and moderate flow velocities. Coussot and Meunier (1996) similarly discriminate fluid mass movements using rheological criteria. The basis of their classification is an assessment of the solid fraction range (sediment concentration) and material type (sediment composition). The solid fraction is the percentage volume that is composed of solids. The material type distinguishes between cohesive materials (clays) and non-cohesive (granular) materials (Figure 2.7). This classification is conceptually superior to the one presented by Pierson and Costa (1987) as it allows for changes in sediment composition. However it is still difficult to apply, owing to its qualitative nature.

Figure 2.6: Rheological classification of sediment- water flows and flow nomenclature. Vertical boundaries A, B and C are rheologic thresholds and are a function of grain size distribution (here assumed to be a coarse and poorly sorted mixture) and sediment concentration. Moving left to right, boundary A marks the onset of yield strength; boundary B marks the sudden, rapid increase in yield strength which permits static suspension of gravel and the onset of liquefaction behaviour; boundary C marks the cessation of liquefaction behaviour. Horizontal velocity boundaries, also a function of grain size distribution and sediment concentration as well as particle density, are determined by how stress is transmitted between particles during flow (after Pierson & Costa, 1987, p9).



FLUID TYPE	NEWTONIAN	NON-NEWTONIAN		
INTERSTITIAL FLUID	WATER	WATER+FINES		WATER+AIR +FINES
FLOW CATEGORY	STREAMFLOW		SLURRY FLOW	GRANULAR FLOW
FLOW BEHAVIOR	LIQUID	PLASTIC		

Figure 2.7: Classification of mass movements on steep slopes as a function of solid fraction and material type, from Coussot and Meunier (1996, p216)



Both the rheology-based classifications of flow and mass movements presented by Pierson and Costa (1987) and Coussot and Meunier (1996) are conceptual models based on limited observation, measurement, laboratory experiment, theory, and resultant morphology. As they are only partially quantifiable, they cannot be easily tested. They do, however, illustrate the spectrum of flow processes for the transport of sediment in mountain environments and the main variables determining the variation in flow processes.

2.3.2 Torrents and a morphological continuum

The definition of what a torrent constitutes is the subject of much debate in both public and academic domains. In the UK, media news bulletins consider torrents as fast-flowing surges of water and debris. For example with regard to the canyon accident in central Switzerland in July 1999, the BBC stated: " *reports say a sudden storm swelled the Saxeten brook into a raging torrent, uprooting trees*" (BBC 1999). However, in mainland Europe a torrent is considered the morphological form and not the flow process. In France this view is illustrated by 1:25,000 maps of alpine areas (IGN: les cartes touristiques locales) which name mountain streams and rivers as torrents. A further example is illustrated by Figure 2.8, this is a leaflet issued by Electricite de France (1998), warning of the dangers of sudden water level changes in rivers and torrents.

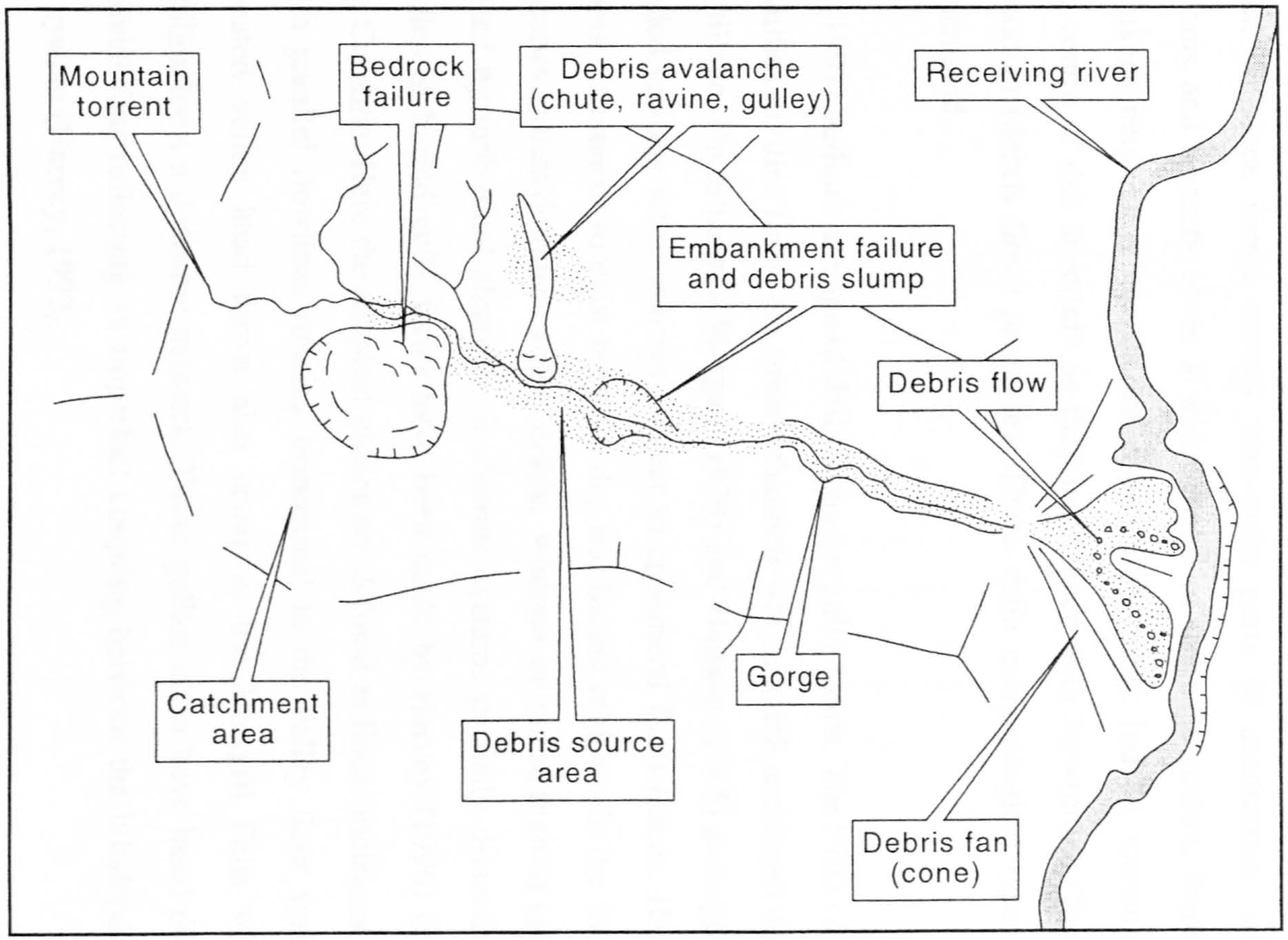
This inconsistency in definition is also in the academic literature. The North American definition considers a torrent a discharge event in a channel, whilst in Europe a torrent is a type of steep mountain stream catchment. Table 2.7 outlines a selection of definitions given by these two schools of thought. This study adopts the European definition, on the basis that it is morphologically based and accommodates scope for processes across the full sediment-water flow spectrum to occur in the same channel. Figure 2.9 shows the main morphological elements of a typical mountain torrent system.

Figure 2.8: Hazard warning leaflet about rivers and torrents (EDF, 1998).

Table 2.7: A list of torrent definitions, categorised as belonging to the European or North American schools.

School of definition	Author(s)	Definition
European	Eisbacher (1982, p12)	"The term torrent as used here refers to a high gradient ephemeral or perennial water course characterised by sporadic discharge of masses of solid debris."
	Eisbacher & Clague (1984, p14-15)	"High gradient ephemeral or perennial water course in mountainous terrain which is characterised by sporadic and sudden discharge of debris."
		"Torrent system consists of three parts, one which generates, another which translates, and a third which receives debris."
	Novak (1994, p148)	"The torrent is a water-course category defined as a stream with highly variable discharge, high slope gradients of the bottom, high scouring activity, transport and deposition of sediment and frequent changes of channel dimensions, the main criterion being the formation, transport and deposition of sediment."
	Schmidt & Ergenzinger (1994, p3)	"A mountain torrent ('Wildbach' in German terminology) has a steep average gradient, but the longitudinal profile consists of sections of different degrees of bed inclination."
		"Mountain rivers and especially mountain torrents are characterised by highly variable discharges and sediment transport volumes with bedload constituting a substantial part of the total load.."
	Rickenmann (1997, p938)	"A torrent is generally characterised as a steep and short stream in sometimes unstable geologic formations and showing a rapid rainfall runoff response."
North American	Swanston & Swanson (1976, p212/213)	"Debris torrents involve the rapid movement of water-charged soil, rock, and organic material down steep mountain channels... Debris torrents typically occur in steep intermittent first- and second- order channels."
	Hungr *et al.* (1984, p663)	"Debris torrents, which are rapid flows of soil and organic debris down steep mountain channels..."
	VanDine (1985, p44)	"...channelised debris flows, also called debris torrents.."
		"A debris torrent is defined as a 'mass movement that involved water charged, predominately coarse-grained inorganic and organic material flowing rapidly down a steep, confined pre-existing channel."
	Bovis & Dagg (1988, p590)	"Coarse-grained channelised debris flows, also known as debris torrents, are a common occurrence within small, steep catchments.."
	Slaymaker (1988, p567)	"Debris torrents are here defined as rapid, channelised flows of saturated, poorly sorted non-plastic soil and organic debris."

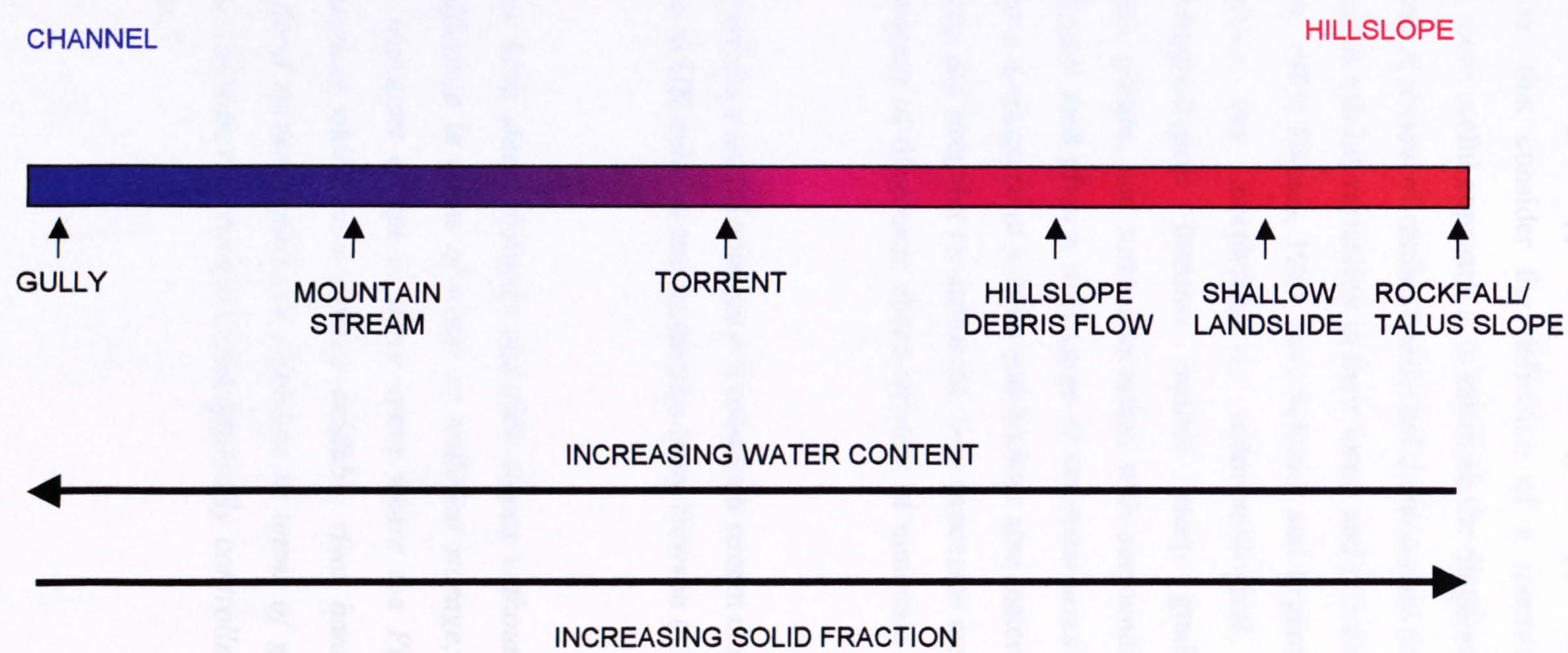
Figure 2.9: The main morphological elements in a typical mountain torrent system (From Eisbacher, 1982, p13).



This study supports the contention that mountain drainage basin torrents are part of a morphological continuum, which is an expression of the sediment-water flow spectrum. This ranges from features that are channel-based to hillslope features (Figure 2.10). The hydrological concept of zero-order basins (i.e. hollows situated in the uppermost portions of 1st-order basins, having no channels and only drain sporadically (Tsukamoto *et al.*, 1982, and Tsuboyama *et al.*, 2000)), is of value in helping to explain the morphological continuum. Small channel features such as gullies and the hillslope forms occupy zero-order parts of catchments, whilst mountain streams and torrents cover a wider range of drainage orders, therefore providing a linkage between hillslopes and downstream areas. Indeed, torrents are located in the centre of this spectrum as they experience both Newtonian (fluvial) and non-Newtonian (debris flow) processes. These main morphological types are now briefly discussed.

Gully: Bocco (1991) outlines a range of definitions for gully forms. The FAO (1965) indicate that gullies in tilled fields are stream channels whose width and depth do not allow normal tillage. On hillslopes Morgan (1979) and Hudson (1985) state gullies to be steep sided eroding water courses subject to ephemeral flash floods. Harvey (1992) considers differences to exist between dry and humid regions. In the former badland landscapes gullies dominate entire slopes, whereas in humid regions gullies are characterised by individual channels or discrete systems partially dissecting a hillslope. Studies of humid gully forms have been made by Harvey (1996) in the Howgill Fells, Cumbria. Here the simplest gullies are defined as linear incisions into hillslopes, with parallel flowlines running orthogonal to the valley floor system. More complicated valley head forms also occur in the Howgill Fells where convergent gullies form a dendritic network. These gullies often have basal debris cones and alluvial fans reflecting an imperfect coupling between the hillslope and basal channel system (Harvey, 1992).

Figure 2.10: The morphological continuum of mountain drainage basins, with water and solid indicators from Coussot and Meunier (1996).



Mountain streams: Milhous (1994) asks the question: 'What is a mountain river?' and in reply states a mountain river is a river located in a physiographic unit called mountains. Such a tautological approach is unhelpful, especially in the light of previous discussions that consider the definition of a mountain is itself not straightforward. A more useful approach is to establish the diagnostic characteristics of mountain streams. A review of studies conducted on mountain streams establishes that mountains streams exhibit variability in their forms and processes (for example, Newson and Leeks, 1985; Davies, 1989; and, Schmidt and Ergenzinger, 1994) but still possess certain key morphological, sedimentological, and hydraulic characteristics. Morphological features include steep gradients, step-pool longitudinal profiles, gorges, and some interaction with surrounding hillslopes. In relation to the sediment load often a wide range of sediment sizes are evident from silt to boulders, but a dominance of cobble and boulder size material prevails. As a function of this steep and irregular environment, flow processes are turbulent. Table 2.8 provides a summary of diagnostic characteristics of mountain streams noted in the literature.

A definition that provides a useful summary of mountain stream characteristics, with particular reference to UK uplands and mountains is by Newson (1981 p60-61), who states:

"Mountain streams have steep channels and side slopes without any intervening floodplain of significance in terms of water or sediment storage; a dominance of bedload sediment transport except in those areas where the Pleistocene legacy includes finer materials which have formed erodable river banks; and a flashy regime in which flood spates apparently dominate in terms of geomorphological effectiveness. Flow resistance is complex and generally controlled by large scale roughness elements."

Table 2.8: Examples of mountain stream characteristics from the literature (NS- no specific study area, is instead a general discussion.)

Author (s)	Study area	Steep gradient	Step-pool	Gorges	Hillslope interaction	Wide range of particle sizes	Cobble./ boulder presence	Turbulent flow regime
Davies (1989)	NS		*	*		*	*	
Newson (1981)	UK	*			*	*	*	*
Newson and Leeks (1985)	English Lake District	*						
Schmidt and Ergenzinger (1994)	NS	*	*		*	*		*
Jaeggi and Rickenmann (1987)	NS	*	*		*	*		
Ergenzinger (1992)	Alps, Germany	*	*			*	*	
Whittaker and Jaeggi (1982)	NS		*					
Jaeggi (1995)	NS	*	*		*	*	*	
McPherson (1971)	Rocky mountains, Canada	*						
Furbish (?)	Front Range, Colorado					*	*	
Hubbard & Thorne (1994)	Colorado	*				*	*	
Takahashi & Sawada (1994)	Japan	*	*		*			
Milhous (1994)	NS	*			*	*	*	
Jarrett (1994)	Colorado	*					*	*
Blizzard and Wohl (1998)	Colorado	*						

Debris flows: A large literature exists on debris flows, covering aspects such as definition; morphological and sedimentological features; preparatory and initiating conditions; flow mechanics and geotechnical properties of materials; geographical distribution and geomorphological impact; magnitude and frequency; dating; and flow hazard and forecasting. Such a breadth of research is beyond the scope of this review, here emphasis is given to the characteristics defining debris flows. For a wider treatment of the subject consult Costa (1984), Innes (1983b), Johnson and Rodine (1984), and Takahashi (1991).

Costa (1988) considers debris flows to be characterised by both geomorphological and sedimentological criteria. The morphological features of debris flows, first described in detail by Sharp (1942), include a combination of sediment source area, flow track, lateral levee deposit, terminal lobes, and possibly a basal fan (for example: Johnson and Rahn, 1970; Pierson, 1980; Rapp and Nyberg, 1981; Costa, 1984; Johnson and Rodine, 1984; Rapp, 1985; Addison, 1987; Slaymaker, 1988; Wohl and Pearthree, 1991; Fannin and Rollerson, 1992; Lewin and Warburton, 1994; Corominas *et al.*, 1996; Coussot and Meunier, 1996). Levees are deposits running parallel to the debris flow track, often occurring on both sides in the form of near-conical mounds of material (Johnson and Rodine, 1984; Steijn *et al.*, 1988). Costa (1984) considers levees to be remnants of lateral areas of flow, which are sheared away from a faster moving central plug of flowing debris. Terminal lobes form where a slowing debris flow halts, and forms a lobate deposit characterised by a steep frontal snout of coarse material followed by a fining tail of matrix supported clasts (Johnson and Rodine, 1984). Idealised levee and lobe forms are shown in Figure 2.11. Sedimentological features indicative of debris flow processes include matrix supported material or poor sorting, no imbrication, no stratification, and inverse grading (Johnson and Rodine, 1984; Wells and Harvey, 1987; Costa, 1988; Davis, 1992; Scott *et al.*, 1995; Coussot and Meunier, 1996). A key characteristic of debris flows is the location of their occurrence or starting zones. Brunsden (1979) and Innes (1983b) classify some debris flows to occur on either a hillslope or being confined in a valley or channel. Takahashi (1981a,b; 1991) outlines possible mechanisms for the generation of debris flows in these two situations. On slopes the initiation mechanism consists of oversaturation of loose debris; however in valley bottoms starting mechanisms include liquefaction of the streambed or the sudden

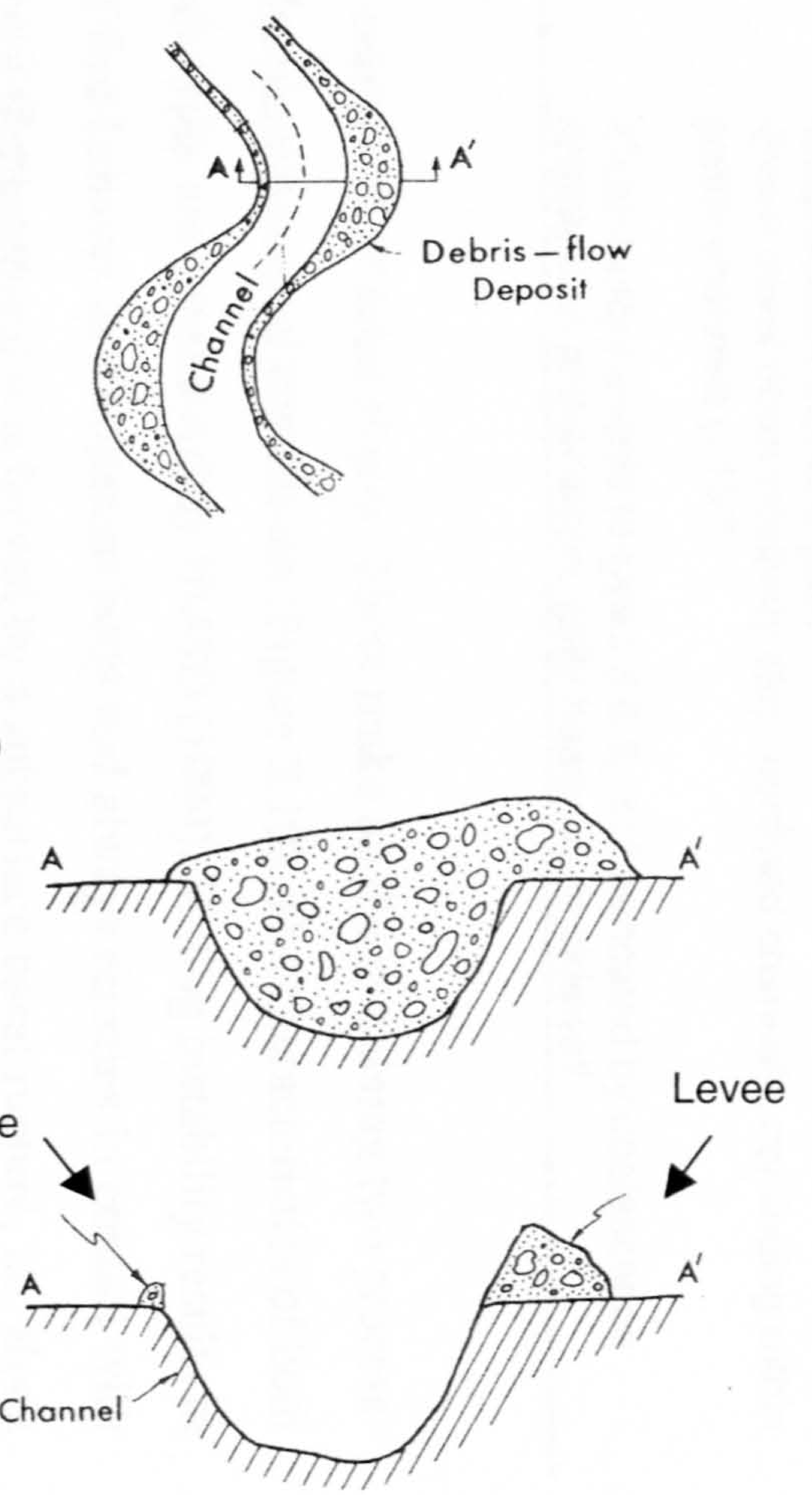
Figure 2.11: Idealised debris flow deposits, (1) levee and (2) lobe. (Adapted from Johnson and Rodine, 1984).

(1) (a- plan view ; b- cross when debris flow occupied channel; c- cross section once debris flow passed through, showing levees.)

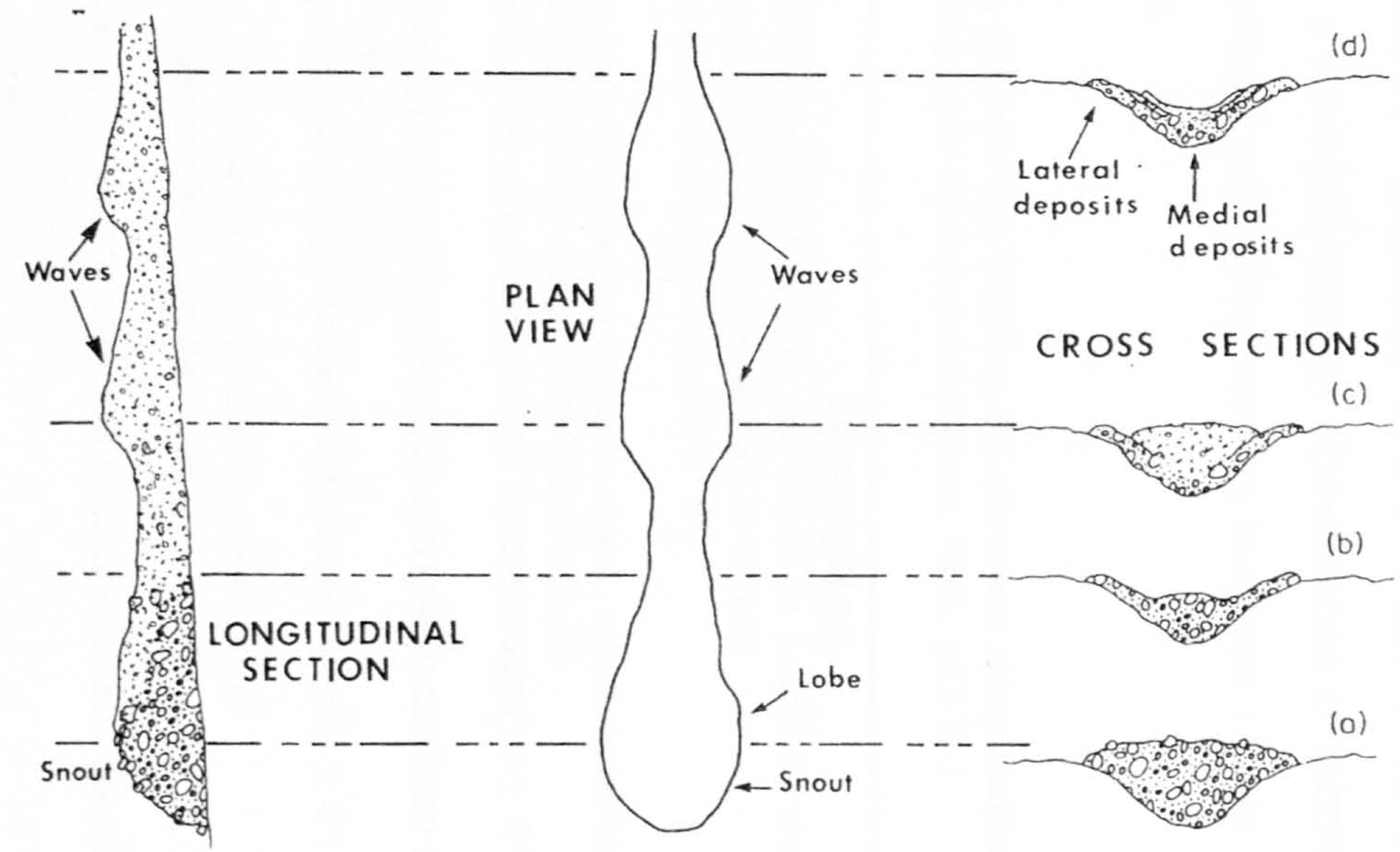
(a)

(b)

(c)



(2)



outburst of water and debris (Takahashi, 1981a). More recently Fannin and Rollerson (1992) propose a sevenfold category classification of debris flows around the basic principles of hillslope and valley starting locations (Table 2.9), although would be difficult to apply.

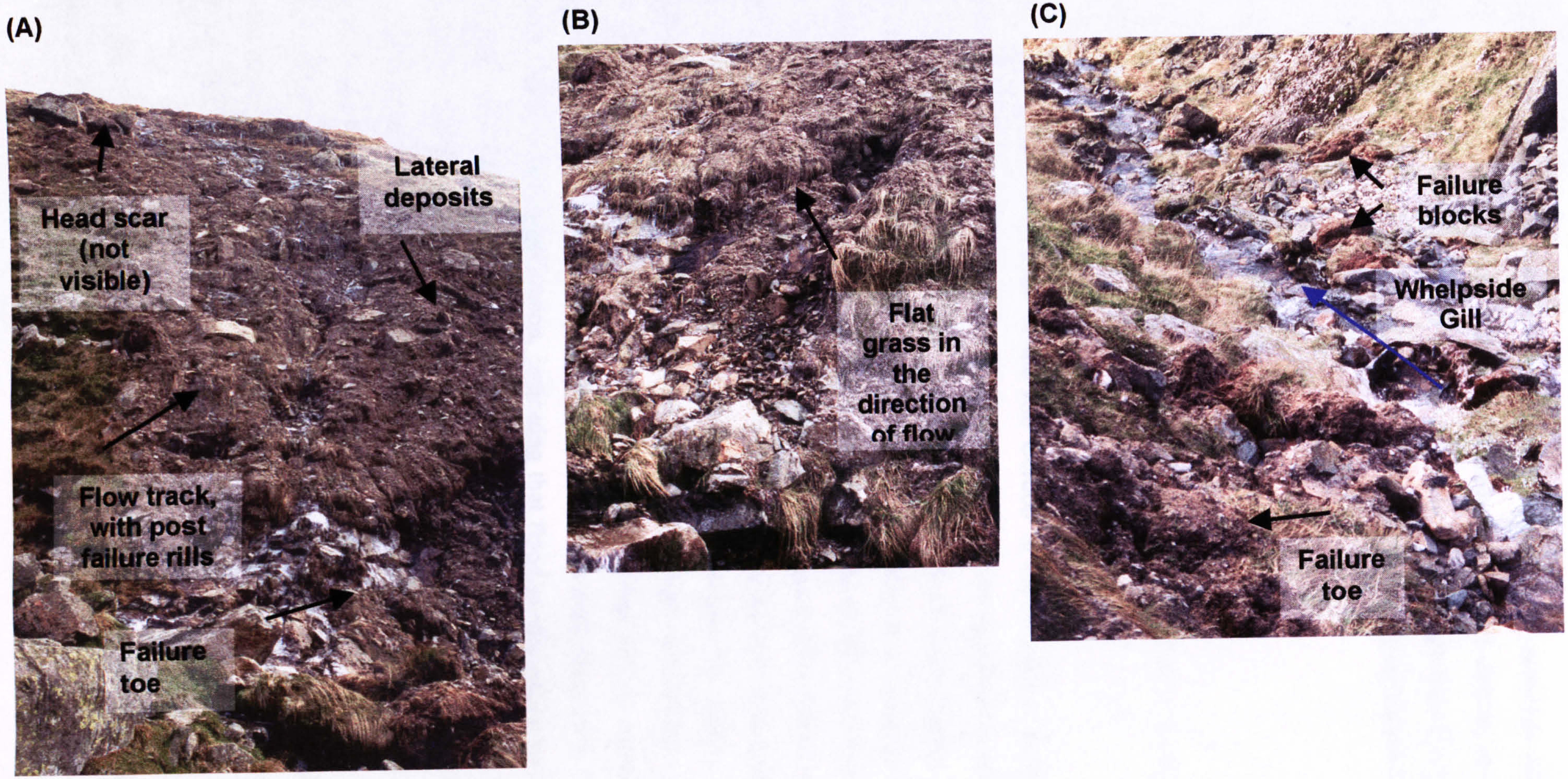
Table 2.9: Classification of debris flow initiation and movement using morphological criteria from British Columbia (Fannin and Rollerson, 1992, p73-75.)

Classification	Description
Type 1	-Single events which initiate and travel on a uniform slope -Slide movements are rare except in source -Deposition on planar slope (15 ± 8°)
Type 2	-Single event initiated on an open slope, enters or initiates in a gully -Event travel down steep/ confined channels -Deposition on steep/ unconfined fans at base (12 ± 6°)
Type 3	-Same as type 2, but continuation of travel in confined channels but or less slope (5-15°) -Deposition on gentle/ unconfined fans at base (7 ± 4°)
Type 4	-Single event initiated on a steep gully sidewall -Terminates on floor of gully (< 20°)
Type 5	-2+ events, initiated at separate locations on an open slope, then entering or initiating a gully -Channel gradient >15° -Deposition occurs on steep, unconfined fans at base of gully -Occasional deposition in channel of gully
Type 6	-Same initiation as type 5 -Coalescence into one path -Event travel down relatively step, confined channels, continuing within gentle channels (<15°)
Type 7	-Contributory events to types 5 & 6, but truncated by coalescence -Initiated on planar slope, gully headwall or sidewall

Shallow slides and rockfall/ talus slopes: These make up the remaining two process-form units of the morphological continuum (Figure 2.10). The characteristics of both mass movements types are considered by HMSO (1994). Sliding instability results in a moving mass that behaves as a coherent body and always remains in contact with the ground, where displacement is achieved by a subsurface basal rupture, i.e. along a shear plane. Whilst there are many forms of slide a number of common morphological features include a crown (discontinuity between unbroken and slide failure surfaces at the highest point), head scar (high gradient incision beneath the crown caused by the break up of the pre-failure surface) and debris deposits. HMSO (1994) states the term 'shallow' is a category referring to the depth of the basal shear surface, which has no accepted definition but normally has a depth to length ratio of 0.01 to 0.15. Such landslides are often of a translational nature, i.e. have a shear surface sub parallel to the ground surface. These failures may also exhibit evidence of flow as slide blocks disintegrate. Such flowslides are a complex form of landslide where displacement is achieved by more than one mass movement type, reflecting that mass movements are themselves a continuum of process-form activity (HMSO, 1994). A local example of such slide-flow process activity is illustrated by Figure 2.12 (photographs taken 18th November 1999), this shows a very fresh failure to the south west of Helvellyn, adjacent to Whelpside Gill (G.R. NY 330 150, c. 570 m O.D.). Field observations identified a shallow head slide scar approximately 11m long and 5.5 m wide. Around the crown tears in the ground surface possibly indicate a build up in stress prior to slide failure. The modification of the slide into a flow of material is suggested by the smoothing of grass in a downslope direction and lateral block lines (Figure 2.12 [A, B]). This failure is likely to have occurred in response to the heavy rainfalls of 4-5th November 1999, for example, 177 mm of rainfall was recorded at Seathwaite over 2 days (Eden, 1999). Supporting the idea of failure at this time, are the existence of fresh failure blocks in the channel below and immediately downstream of the failure toe (Figure 2.12 [C]). If the failure occurred prior to the 4th November it is likely that such deposits would have been washed away.

Falls of material occur when rocks become detached from high-angle scars and cliffs, therefore descending through the air due to gravity. The prefix 'rock' describes the material involved in this process. Talus deposits are evidence of such displacement, and are sloping accumulations of rock fragments on areas of reduced gradient beneath cliffs (Goudie, 1990; Ballantyne and Harris, 1994). Ballantyne and Harris (1994) distinguish talus from scree, stating that scree generally refers to any slope cover of coarse debris irrespective of location.

Figure 2.12: Fresh shallow slide-flow in Whelpside Gill (Photographs taken 18.11.99). The flow zone (A), smoothed grass near toe (B), and failure blocks in the channel (C)



The foregoing provides an overview of the characteristics of mountain fluvial systems. However, the difference between mountain streams and torrents are less obvious. Some authors use both terms in the description of a single drainage basin, for example Ergenzinger (1992, p416) in reference to the Lainbach catchment in the northern Alps states-

"...the Lainbach, a very steep mountain river in upper Bavaria"

"The Lainbach, which has an average gradient of 0.02 is defined as a 'wildbach', i.e. a steep mountain torrent.."

Similarly Billi *et al.* (1995) refer to the Rio Cordon in the Dolomites as both a mountain stream and torrent. Such loose application of terminology fails to account for an understanding of the features distinguishing each of these forms. Both Eisbacher and Clague (1984) and Jaeggi (1995) recognise the existence of a difference in terms of process activity. Eisbacher and Clague (1984) consider that a torrents' ability for sudden transport of debris sets them apart from creeks which discharge from basins in more subdued terrain. Jaeggi (1995) suggests that mountain streams contrast with torrents, as the latter are dominated by debris flow phenomenon. However this concept of dominance is not defined, and therefore could refer to frequency of process type, sediment transport volume, or the amount of geomorphic work. Rickenmann (1997) with regard to sediment transport in six Swiss torrents provides further qualification, indicating that flood events with substantial bedload occur frequently, but debris flows are generally more disastrous. These process divisions whilst acknowledging a difference between mountains streams and torrents do little to emphasise morphological differences. A steep gradient, step-pool profiles, a wide range of particle sizes, gorges, and the supply of material from hillslope source areas is common to both mountain streams and torrents. The critical feature between the two is the existence of a basal fan in a torrent. Indeed Eisbacher and Clague (1984, p15) state:

"Debris fans (or cones) are the most conspicuous manifestations of active or dormant torrent systems."

The existence of fans supports the idea that debris movement in torrents is very active (Emmanouloudis, 1992; Schmidt and Ergenzinger, 1994) and the associated occurrence of channelised debris flows is more likely, though not necessarily exclusively limited to torrents (Jaeggi and Rickenmann, 1987; Davies, 1989). Hence torrents and to a lesser extent mountain streams are important components of mountain basins, as their position in the landscape provides a linkage for the downslope movement of debris released by hillslope mass movements (Eisbacher and Clague, 1984; Takahashi and Sawada, 1994; Milhous, 1994; Schmidt and Ergenzinger, 1994). Finally an illustration of theses morphological forms is shown in a series of aerial photographs from the northern and central Lake District (Figure 2.13); these give a local context to the preceding discussion.

2.3.3 Torrent research

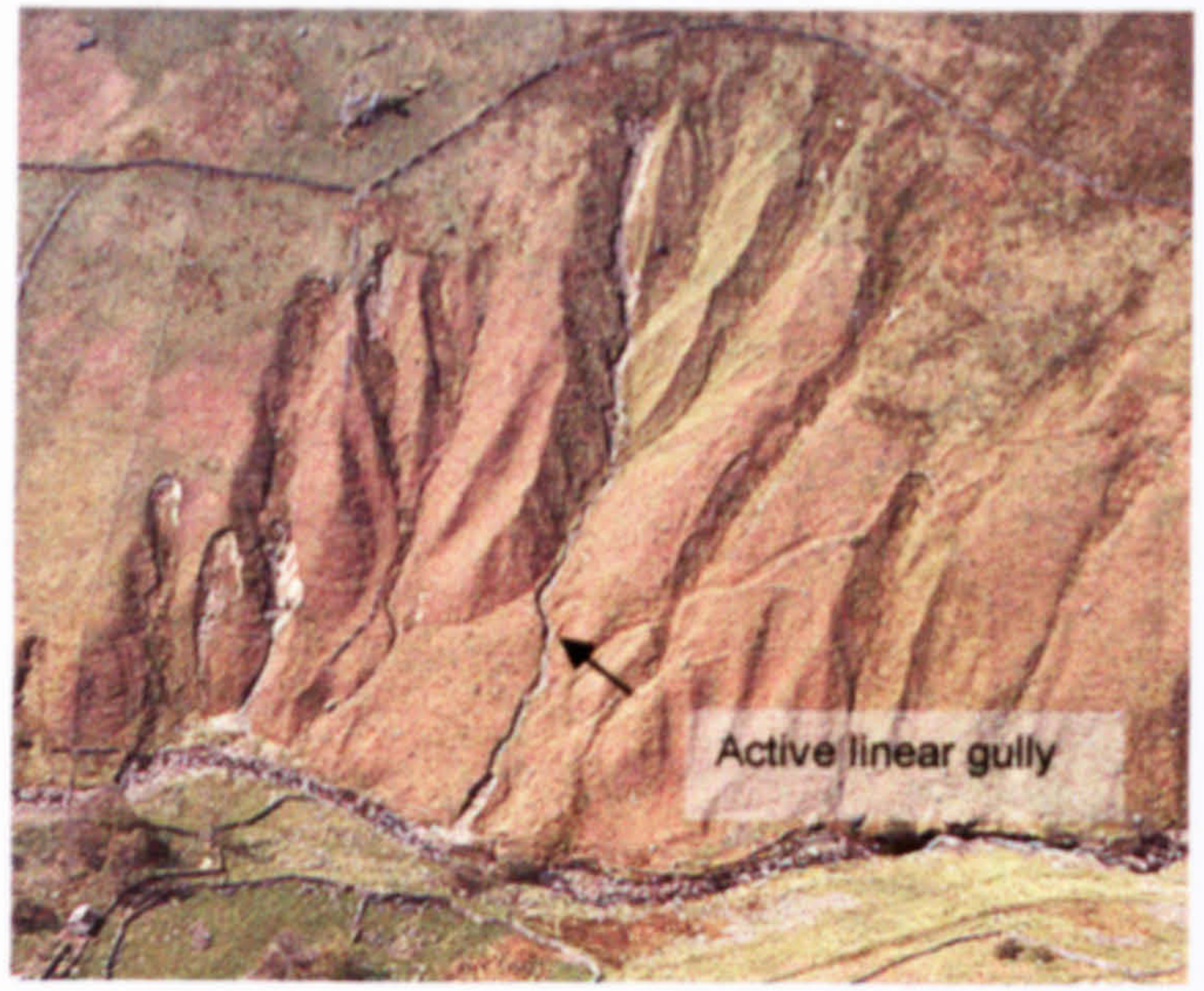
2.3.3.1 European Alpine research

In considering sediment dynamics in torrents, Kronefellner-Kraus (1982, p269) invokes the term 'torrent erosion', which is taken to embrace all erosion phenomena related to sediment discharge including soil erosion, landslides, gully erosion, and bedload transport. Torrent erosion is therefore not a specific process but instead a collective term for processes of erosion and deposition occurring within a torrent and its catchment. These processes are part of the sediment-water flow spectrum.

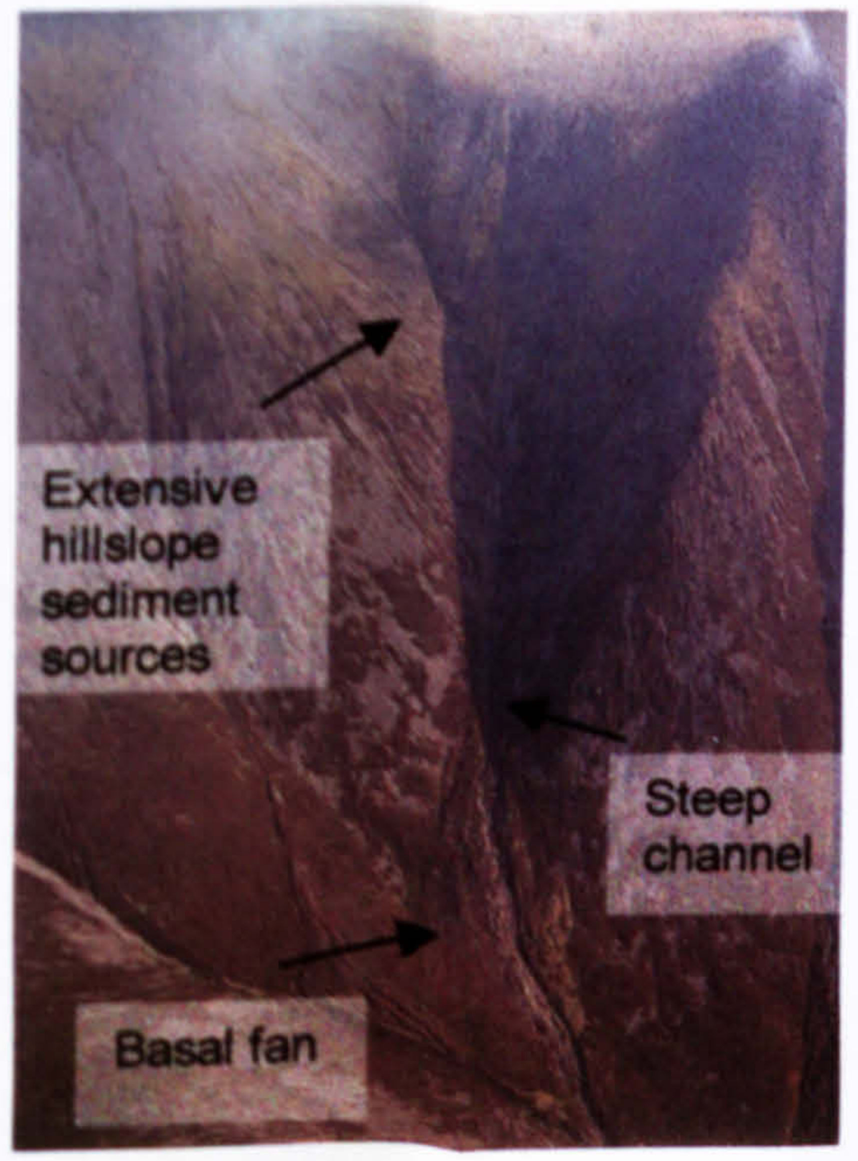
Research investigations of torrents in Europe have largely been driven by the need to gain understanding of these systems for the purposes of planning in mountain areas (torrent control measures and the zoning of danger areas, e.g. Kronefellner-Kraus, 1974, 1982, 1983; Aulitzky, 1994; Schmidt and Ergenzinger, 1994; Boll, 1997; Hegg and Rickenmann, 1999; Universitat fur Bodenkultur, 2001; Universitat Bern, 2001). The focus of research has been on bedload sediment transport and debris flow activity because of the potential threat to downstream fans and the surrounding human infrastructure. Bedload transport investigations have been conducted in a number of experimental catchments, including the Lainbach in Bavaria, Rio Cordon in the Italian Dolomites, and Erlenbach in Switzerland.

Figure 2.13: Morphological continuum of mountain drainage basin features in the Lake District
(A- Gully; B- Mountain stream; C- Torrent; D-Hillslope debris flow; E- Shallow landslide; F- Talus slope.)

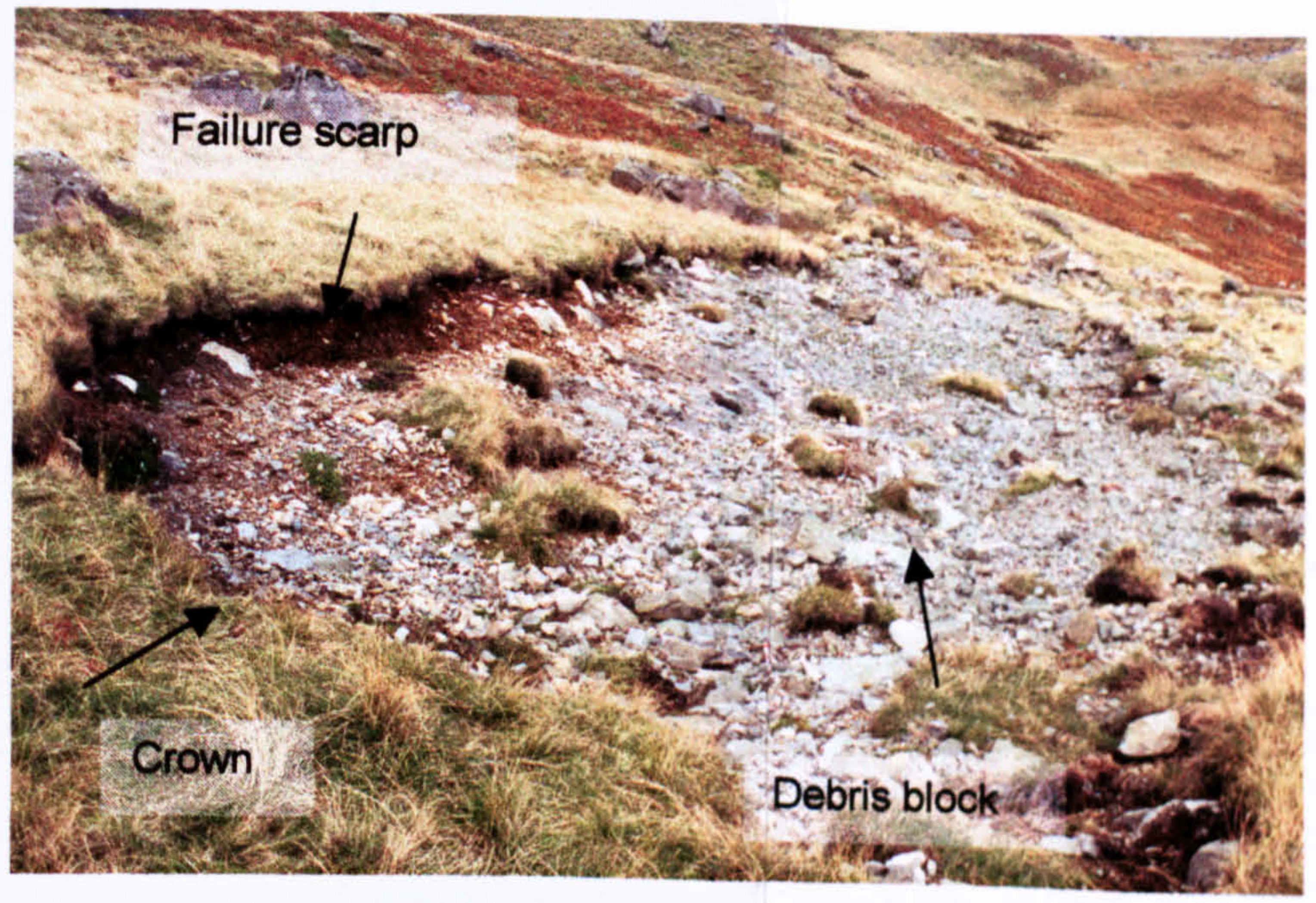
(A) Gullied hillslope at Dowthwaitehead (NY 368 208)



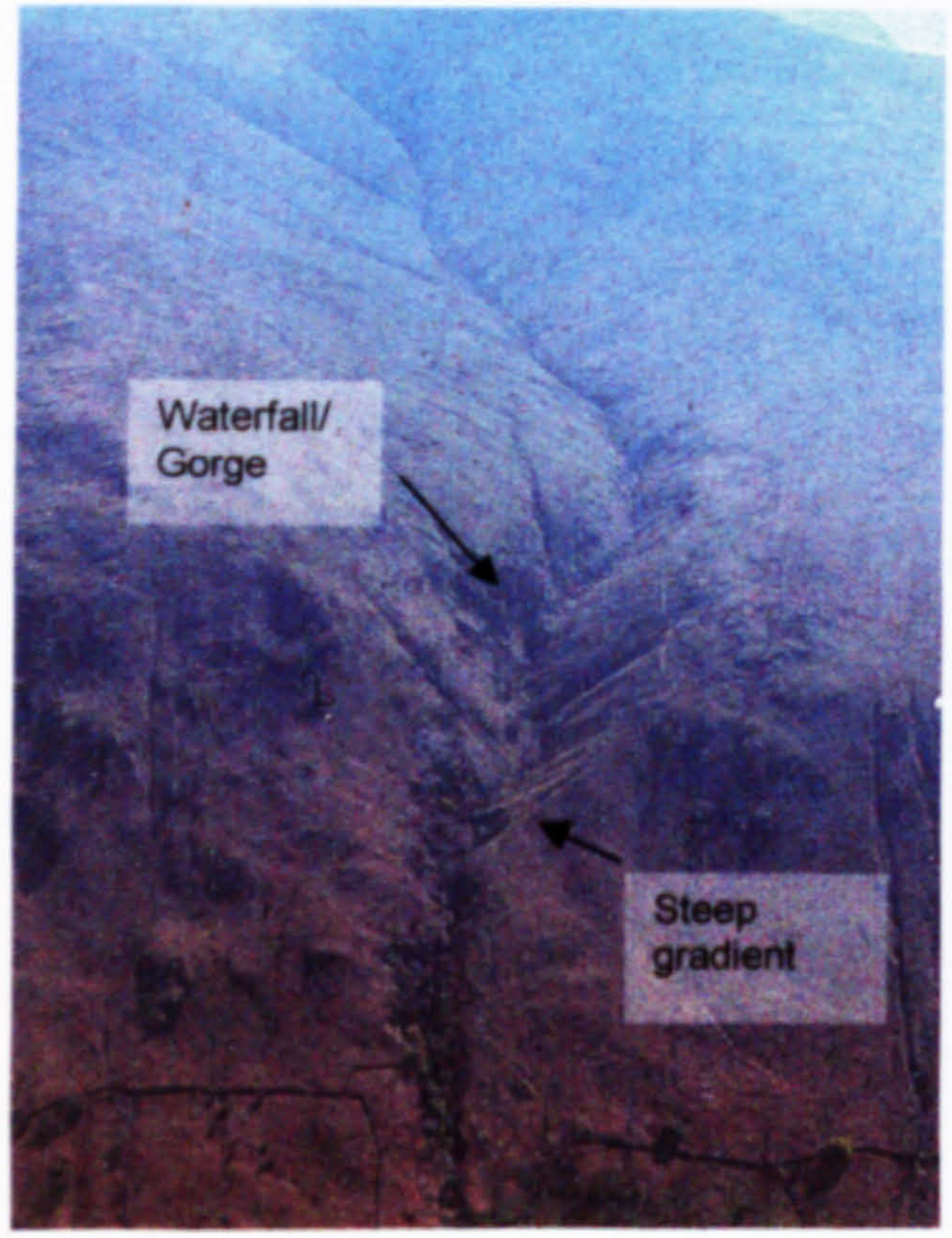
(C) Torrent: Tongues Beck (NY 260 277)



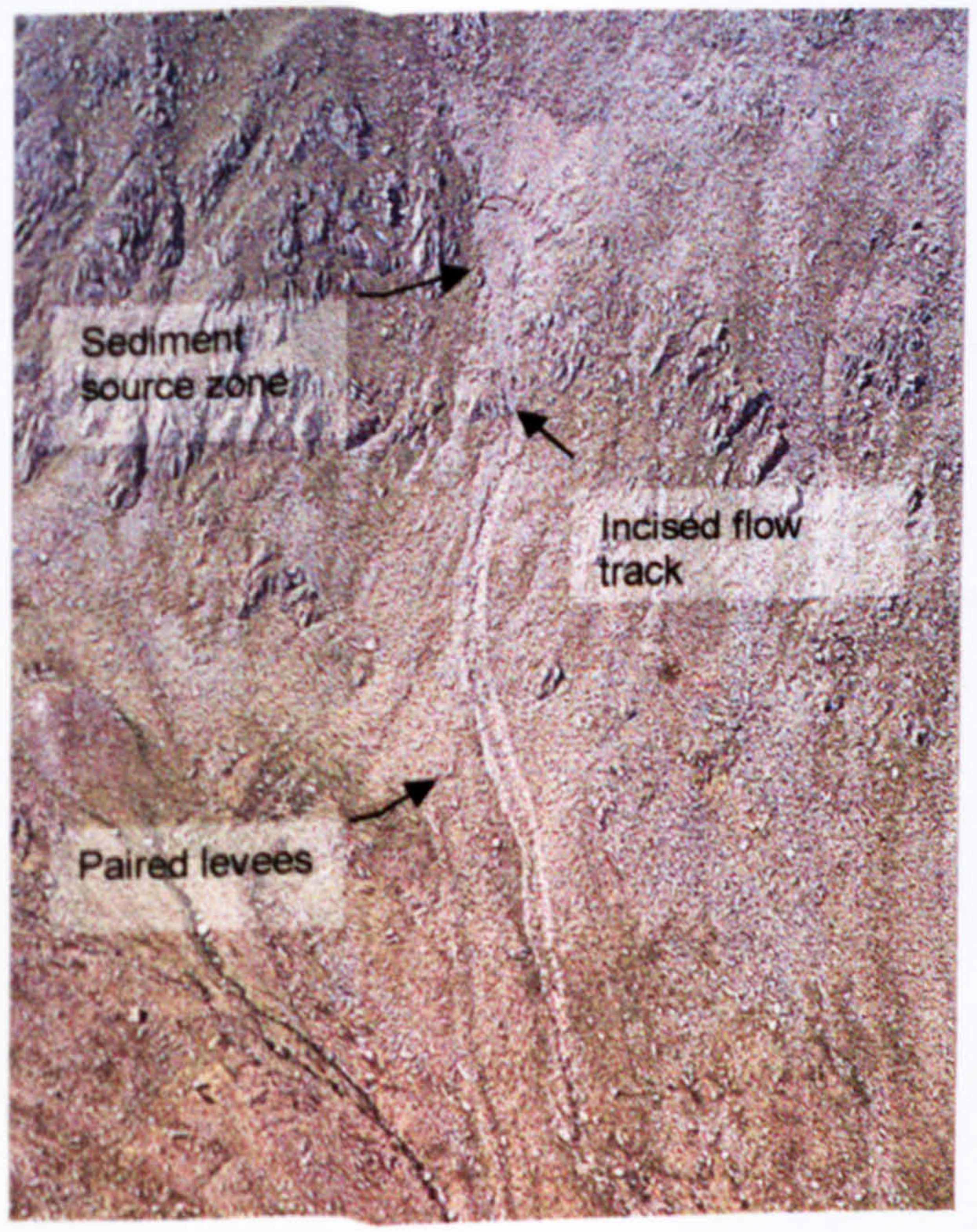
(E) Shallow landslide: Greenhow End, Fairfield (NY 372 121)



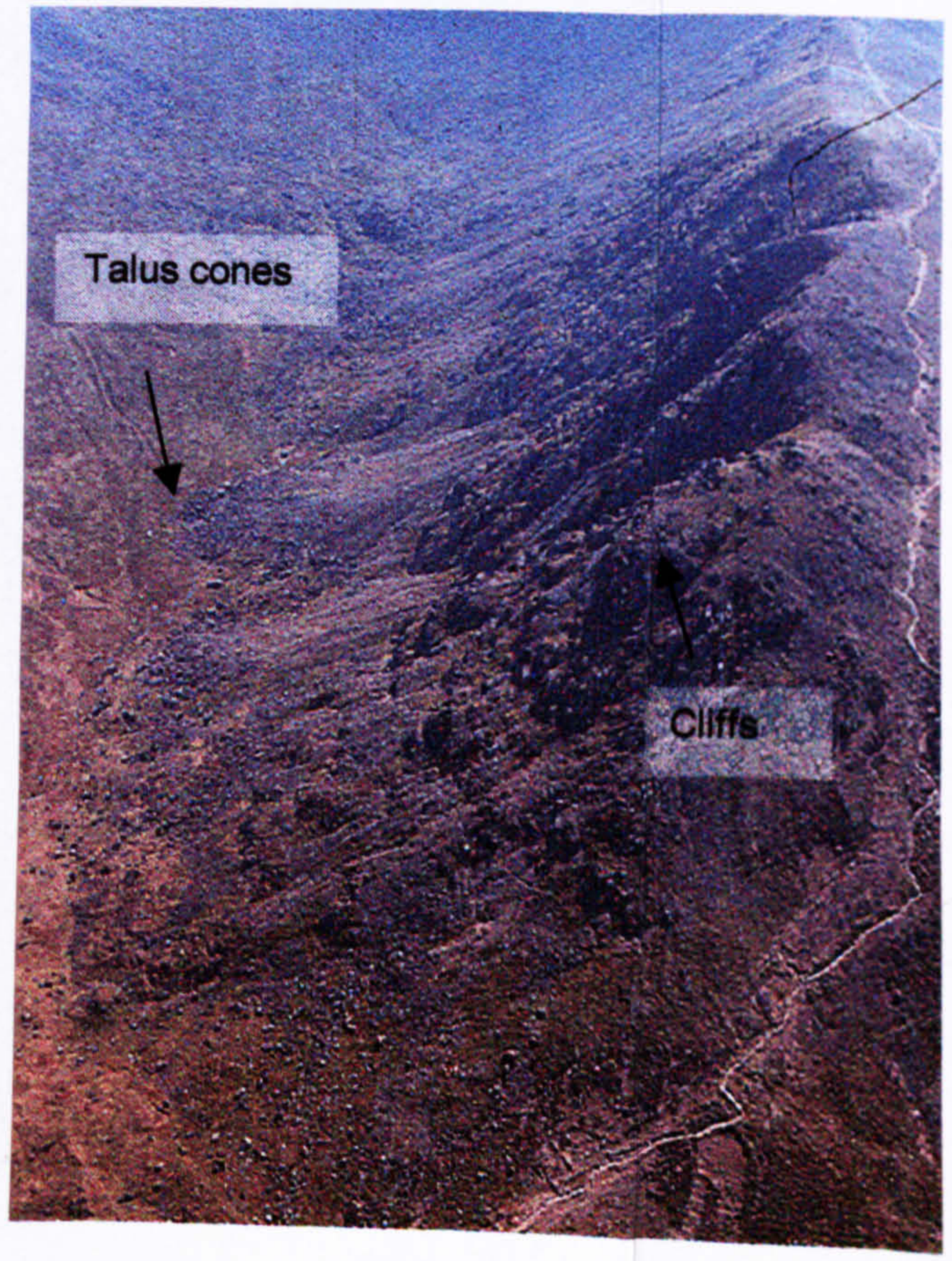
(B) Mountain stream: Stanah Gill (NY 330 190)



(D) Hillslope debris flow: Brown Cove (NY 341 158)



(F) Talus slope: Browncove crags (NY 332 159)



Schmidt and Ginz (1995) used artificial magnetic tracers in the Lainbach to study the impact of particle mass (size) and shape on sediment transport. This investigation was necessary, as the transport mechanisms in torrents are poorly understood because of the highly variable grain size distributions and irregular bed topography. It was demonstrated that coarser particles are preferentially moved during small and moderate flood events, and compact shapes (spheres and rods) travelled the greatest mean distances. Step-pool sequences influenced the probability of particle entrainment. However, during a large flood in 1990, platy shapes moved the same distances.

Rickenmann (1997), Rickenmann *et al.* (1998), Hegg and Rickenmann (1999) also considered the impact of particle size and bed topography on sediment transport in the Erlenbach torrent. Since 1986 hydrophones have been used to measure bedload transport, allowing a comparison of runoff and bedload transport volume (m^3 per minute). Hegg and Rickenmann (1999) recognise three states: one where no bedload transport occurs (which occurs 99.5 % of the time, with runoff < 200 l s^{-1}); a transitional state where the relationship between runoff and bed load transport is extremely variable; and finally a higher runoff state (i.e. >2000 l s^{-1}) with transport correlated linearly with runoff. The variability in the transitional zone is considered to be a function of the wide range of particle sizes.

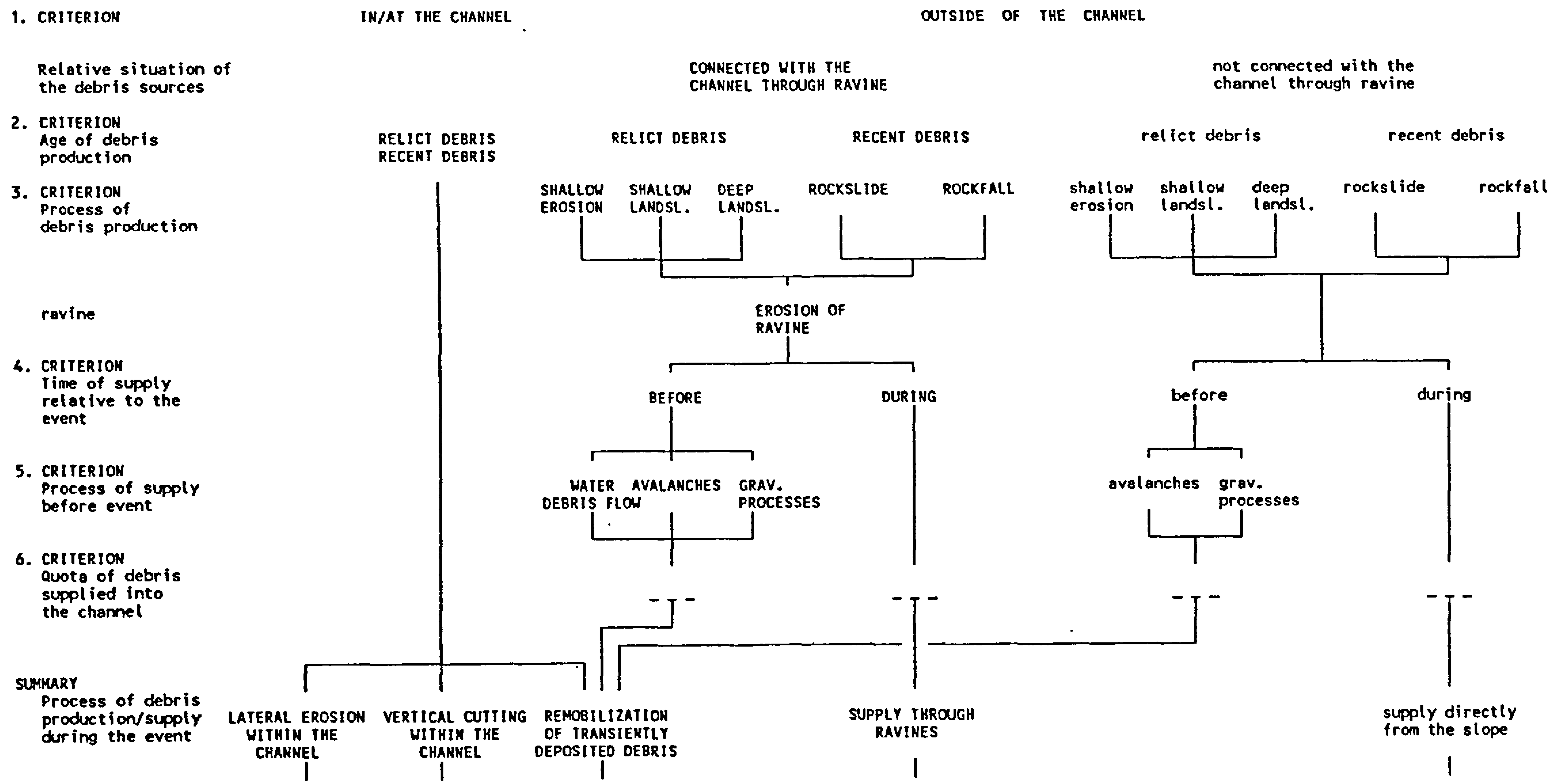
At the Rio Cordon in northern Italy, the monitoring of yields of coarse (> 20 mm) and fine gravel (< 20 mm) are recorded (Fattorelli *et al.*, 1988; Billi *et al.*, 1995, Lenzi *et al.*, 1999). The coarse material enters a trap where ultrasonic probes measure the volume of material at set time intervals (every 10 minutes). The continuous measurement of the finer material is performed by load cells. This monitoring station allows sediment yields under different water discharge conditions to be estimated. From this it has been established that the critical flow discharge for bedload mobilisation in this catchment is 2 m^3 s^{-1}, which can be used to test bedload sediment transport formulae (Billi *et al.*, 1995; D'Agostino and Lenzi, 1999, Lenzi *et al.*, 1999). Like the results of Hegg and Rickenmann (1999), it was found that the success of predicting sediment transport thresholds in torrents depends on whether entrainment occurs under conditions of selective transport or equal mobility.

Research on channelised debris flows in torrents has been conducted in both instrumented catchments, and also in response to storm events (Kienholz *et al.*, 1991; Lewin and Warburton, 1994). The Moscardo torrent in the Italian Alps has been identified as being prone to debris flow activity and provided an opportunity to conduct instrumented studies of debris flows (Arattano and Moia, 1999; Arratano and Marchi, 2000; and, Massimo, 2000). Arratano and Marchi (2000) used ultrasonic sensors and a video camera triggered by one of the ultrasonic sensors to monitor debris flows in the torrent. Mean front velocity measurements are derived from both instruments and show differences of less than 9 %. Seismic detectors placed in the same torrent up and downstream of the fan apex recorded the passage of debris flow events (Arratano and Moia, 1999; Massimo, 2000). The debris front causes a peak in ground vibration velocity, the strength of which is a function of the flow depth and the grain size distribution. The vibrations are only consistently registered on the fan. Similar studies have also been conducted in Japan (Itakura *et al.*, 2000).

For some time there has been awareness that studies of torrent erosion should be more holistic, i.e. incorporate the whole range of basin processes contributing to the operation of sediment discharge in a torrent, specifically the role of slope processes (Kronefellner-Kraus, 1982, 1983; Whittaker, 1986; Fattorelli *et al.*, 1988; Kienholz *et al.*, 1991; Aulitzky, 1994; Schmidt and Ergenzinger, 1994; Billi *et al*, 1995; Boll, 1997). However, attempts so far have been of limited scope. Some studies, i.e. Rickenmann (1997) and Batella *et al.* (1999) make reference to slope process, but the emphasis of their investigations is on channel processes. More detailed studies have been performed by Kienholz *et al.* (1991); Schmidt (1994); Billi *et al.* (1995); Hegg *et al.* (1996).

Kienholz *et al.* (1991) studied the bedload balance of 21 Swiss torrents following 1987 summer storm events. Based on their observations a model of sediment source location and delivery was proposed (Figure 2.14). Field survey and geomorphological observations indicate the dominance of channel source material (83% average volumetric contribution), of which 60 % is due to vertical downcutting and the remaining 23% from lateral undercutting of embankments. The remaining 17% is of slope origin, the majority (14%) from ravines. Schmidt (1994) undertook a similar exercise for the June 1990 storm in the Lainbach. A comparison of pre-flood

Figure 2.14: Model of bedload production and bedload supply in mountain torrents, from Keinholz *et al.* (1991)



(1984) and post-flood (1990) longitudinal surveys of the torrent bed revealed that 55,000 m^3 of material of non-channel origin was deposited in the channel network. The potential that some of this sediment accretion occurred before the 1990 flood is discounted as observations of bar morphology and channel cross sections reveal no change. Experimental plots reveal forested slopes yielded 7-10 t ha^{-1} during the storm, whilst unvegetated slopes yielded 20-25 t ha^{-1}. Once extrapolated to the entire catchment area, a volume of 13,000 m^3 or 24 % of the channel accretion is accounted for. Other local slope failures and rilling occurred but the majority of the sediment supply is considered to have been obtained from the vertical and lateral erosion of tributaries. Hence Schmidt (1994) shows that under storm event conditions the Lainbach torrent system behaves in a similar fashion to those investigated by Kienholz *et al.* (1991).

Billi *et al.* (1995) in the Rio Cordon study catchment also consider the role of sediment supply from slopes to the torrent channel. A GIS of the catchment shows that only 5.2 % of the total basin area is occupied by active slope sources (defined as bare slopes, overgrazed areas, shallow landslides, and eroded stream banks). Of these areas only 11 % are connected to the drainage network. Measurements and observations of slope sources prior to and following a large flood in September 1994 revealed that many were reactivated, but few new sources were created. Only those sediment sources near channels contributed sediment to the channel. However, no quantification of the sediment yield was provided.

The studies outlined above have identified the important role of slope processes in torrent erosion. However, most of these studies focus on the impact of individual storm events and do not always discriminate the activity of different slope processes. Thus a logical development would be to conduct detailed sediment budget studies of the role of both channel and slope erosion processes over a prolonged period of time. This would allow temporal variations in process type and rates to be monitored and enable the real significance of storm events to be determined.

2.3.3.2 United Kingdom research

Torrents are important landscape features in upland and mountain areas of the UK. Firstly, as these catchments receive large annual rainfall totals, the runoff provides an important water resource, for example Raise Beck in the central Lake District feeds into Thirlmere reservoir. The associated sediment yields are an issue in terms of water quality and the operational life of water storage reservoirs (Butcher *et al.*, 1992; Butcher *et al.*, 1993, White *et al.*, 1996). Secondly, during flood conditions out-of-channel flows of water and debris can cause disruption and damage to nearby infrastructure (e.g. Raise Beck flood of January 1995). The blockage of roads, damage to walls and buildings, and the loss of livestock have major financial implications. The Department of Environment review of erosion, deposition, and flooding in Great Britain (DoE 1995 a, b) considers the impacts of flash flooding in upland and mountain areas, but makes no specific reference to torrents. The only explicit studies of torrents, or indeed torrent erosion in the UK are the Allt Mor torrent in the Cairngorms (McEwen and Werritty, 1988), and Afon Porth-Llwyd in North Wales (Fearnsides and Wilcockson, 1928). McEwen and Werritty (1988) reconstruct the conditions of a flood in August 1978 using meteorological records and palaeohydrological methods. The geomorphological impacts of the flood on the channel and hillslopes are considered. The 1978 event reactivated hillslope failures providing rapid supply of material to the channel, with channel widening, entrenchment and accretion occurring in the lower gradient reaches. McEwen and Werritty (1988) do not provide quantitative assessments of the channel and hillslope sediment yields for the 1978 storm. They do, however, acknowledge that it is not just storm events that are important for sediment transfer in torrent basins: in the case of Allt Mor less active hillslope processes, namely rilling and sheetwash operating during inter-flood periods are also significant. Inter-flood slope activity supplies sediment, which is stored in cones that are subsequently eroded by flood events. This finding is consistent with non-torrent hillslope-channel interactions studied in the UK. Indeed Harvey (2001) shows that over a 30-year monitoring period the coupling of gully debris cones to basal fluvial systems in the Howgill Fells is similar. Frequent sediment production events lead to the enlargement of cones at the base of gullies, with stream floods capable of entraining these deposits occurring every 2- 5 years. Eventually gullies de-couple from the basal stream and rapidly stabilise by revegetation (Harvey, 1992). However, at a large scale the role of rare floods, induces system-wide destabilisation, causing significant hillslope and channel changes. The November 1925 flood in Afon Porth- Llwyd is an example of such an occurrence. Two successive dam bursts in the Llyn Eigiau reservoir and the Code-ty reservoir released substantial amounts of water into the head of the Afon Porth-Llwyd. Fearnsides and Wilcockson (1928) provide a detailed description of the flood impacts, below the lower Code-ty reservoir. Here a gorge falls 800 ft in less than half a mile (244 m in less than 800 m), until it reaches the valley floor where there is a rapid reduction in gradient. Prior to the flood the gorge channel was covered in boulders and heavily vegetated. Post-flood the bedrock channel and bank sections were swept clean, and moraine bank sections were heavily eroded releasing many large boulders. At the base of the torrent the hamlet of Porth Llwyd was buried under a boulder fan up to 40 ft deep (12m), containing boulders in excess of 500 tons (508 tonnes).

This review has established a need to monitor processes in torrent catchments. The dearth of research in the UK probably reflects a lack of appreciation of torrent systems; the difficulty and costs of upland investigations; and the low relative relief of these areas compared to locations such as the European Alps. Unlike Alpine environments where winter conditions (specifically seasonal snow cover) restrict the operational length of field monitoring, the less extreme nature of UK mountains lends itself to study over a full year.

2.4 Techniques for the study of contemporary and palaeo torrent erosion

Table 2.10 lists techniques applicable to the study of torrents in the UK. It is not practical to provide comprehensive reviews of all these here, instead attention is given to sediment budgets and palaeohydrology as these are the main techniques used in the Lake District investigations. Details of the other techniques are considered in subsequent chapters as indicated by Table 2.10. The review that follows provides definitions of the various techniques and examples of applications.

Table 2.10: Techniques applicable to the study of torrent erosion, in the English Lake District, with an indication where techniques are considered in this thesis.

Aspect of torrent erosion for investigation	Study techniques	Location of consideration in this thesis
1. Slope and channel interaction, with a consideration of spatial and temporal aspects	SEDIMENT BUDGET PARTICLE SIZE ANALYSIS	Here and Chapter 5 Chapter 4
2. Reconstruct high magnitude storm events and their geomorphological impact	PALAEOHYDROLOGY LICHENOMETRY GROUND SURVEY	Here and Chapter 7 Chapter 7 Chapter 7 and 8
3. Reconstruct palaeo process histories of buried deposits	PARTICLE SIZE ANALYSIS POLLEN ANALYSIS RADIOCARBON DATING MAGNETIC SUSCEPTIBILITY LOSS ON IGNITION STRATIGRAPHY	As above Chapter 6 Chapter 6 Chapter 6 Chapter 6 Chapter 6
4. A regional study of torrent and debris flow activity	GROUND SURVEY DOCUMENTARY RECORDS (E.G., MAPS, AERIAL PHOTOGRAPHY)	As above Are used in Chapters 5, 6, 7, and 8

2.4.1 Sediment Budgets

Definitions of sediment budgets are offered by Swanson *et al.*, 1982; Dietrich *et al.*, 1982; Lehre, 1982; Lehre *et al.*, 1983; Trimble, 1983; Phillips, 1986; 1987; Loughran, 1992. They all provide similar statements to Reid and Dunne (1996, p3), who state:

" A sediment budget is an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin".

Sediment budget studies in upland and mountain areas have been conducted by Dietrich and Dunne, 1978 (Coast Range, USA); Lehre, 1982 (California, USA); Lehre *et al.*, 1983 (Cascade Range, USA); Stott *et al.*, 1986 (Scotland, UK); Caine and Swanson, 1989 (Cascade Range/ Colorado Front Range, USA); Warburton, 1990 (Swiss Alps); Caine, 1992 (Colorado Front Range, USA) Batalla *et al.*, 1995 (Catalan coastal Range); Llorens *et al.*, 1997 (Pyrenees); Hill *et al.*, 1998 (Hawaii). These examples demonstrate the ability of sediment budgets to identify spatial and temporal variability in sediment movement, and the interaction of hillslope and channel processes.

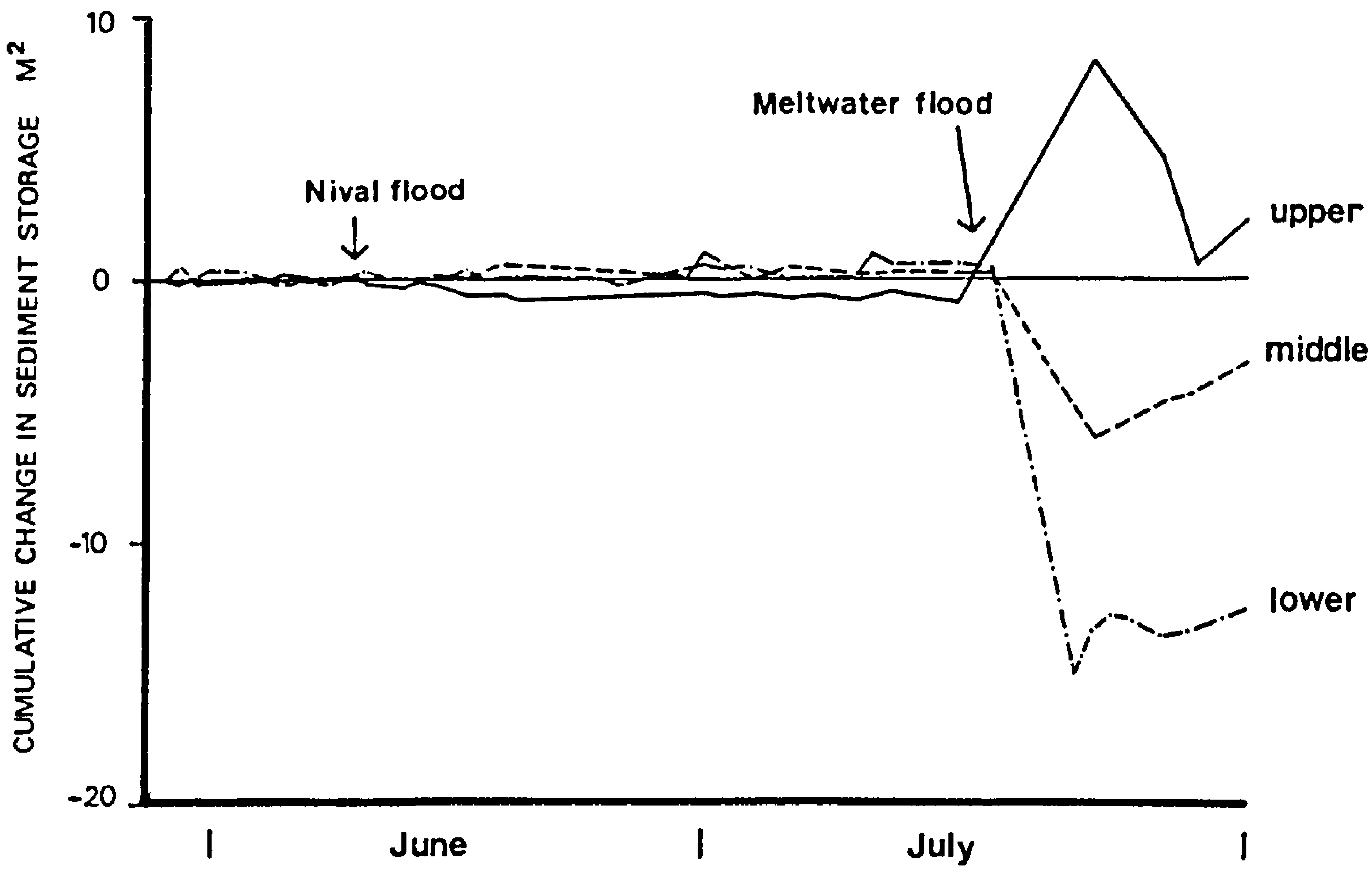
In sediment budgets spatial and temporal variability is manifest at a range of scales. For example, Caine (1992) describes the changing yields of surface sediment transport (runoff and rainsplash) collected by 20 traps throughout the Martinelli snowpatch catchment over 10 years. A dominant flow of sediment is noted in the upper basin, which reduces downslope. This trend is not clearly related to local slope gradient or snow depth, but instead to the extent of vegetation cover. Warburton (1989) in a sediment budget of the proglacial zone of Bas Glacier d'Arolla, also shows spatial variability in process activity. For example, suspended sediment concentration measurements from different tributary streams flows vary from 0 to nearly 8000 m g l^{-1} on a given day. Based on the same study Warburton (1990) also shows the contribution of different processes in the delivery of sediment to the main valley. As process types occur in different locations e.g. hillslopes, sandur bluffs and sandur (moving downslope), a spatial pattern in process activity is indirectly evident. During the monitoring period (2.5 months at start of spring- summer ablation period) hillslopes yielded 11 tonnes, bluffs at the base of hillslope a net loss of 452 tonnes and sandur 4790 tonnes.

Caine and Swanson (1989) compare two small mountain basins, namely H.J. Andrews watershed 10 in the Cascades; and the Martinelli basin in Colorado. Sediment budgets of both systems based on 5-6 years of monitoring identify the absolute rates of sediment production, transport and deposition, with regard to the specific processes. In the inorganic material fraction, soil creep is shown to be an important process in both watersheds: 99 % of mass in movement at watershed 10, and 95 % at Martinelli. However, the delivery of hillslope material to channels shows the dominance of difference processes. At watershed 10, 57 % of inorganic material is transported by debris flows, and the next largest percentage is from dissolved load (27%). In contrast to this at Martinelli, 72 % of inorganic transport is dissolved load and 28 % surface erosion. The actual mass of total sediment transfer is an order of magnitude different in the two systems, in the former channels receive 10.6 t a^{-1}, and the latter 1.3 t a^{-1}.

The sediment budget monitoring studies of Warburton (1990), and Caine (1992) provide examples of temporal variation in sediment dynamics. Warburton (1990) shows that channel erosion of the valley sandur accounted for 95 % of the proglacial sediment supply, which itself is 23 % of the total basin output. The supply of sediment from the valley sandur is highly episodic, as the majority of sediment was supplied during a meltwater flood of July 15-18th 1987. In illustration of the impact of the flood Figure 2.15 (Warburton, 1990, Figure 4) shows the cumulative change in channel cross-sections, and the marked contrast prior to the flood and during the event. With regard to the whole system this event was responsible for 53.2 % of the total material transported from the basin during the study period (25.5.87- 30.7.87). Caine (1992) indicates that surface wash processes at Martinelli exhibit seasonal and inter-annual variability. Sediment movement occurs in the summer after snowmelt on the surface upslope of traps, due to rainsplash and surface runoff. Inter-annual differences are inconsistent and appear unrelated to snow accumulation and cover duration.

A second application of sediment budget studies is the ability to investigate the interaction of hillslopes and channels; examples of this are provided by Stott *et al.* (1986) and, Caine and Swanson (1989). Stott *et al.* (1986) investigate the impact of afforestation and deforestation in paired basins in the Scottish Highlands (Balquidder), i.e. Monachyle Glen (moorland) and Kirkton Glen (coniferous forest). Contemporary rates of hillslope activity were considered to be low or negligible in both basins and therefore were not systematically monitored. However, a shallow landslide in Monachyle Glen during September 1985 provided an opportunity to

Figure 2.15: Detailed channel cross sections of the proglacial stream of the Bas Glacier d'Arolla (27 May- 30 July, 1987) showing cumulative sediment change in storage (Warburton, 1990, Figure 4)



consider the interaction between slope and channel processes. The slide scar was estimated to be 36 m^3 or 65 tonnes of sediment. This travelled down a tributary gully (500 m) terminating in a cone at the junction with the main channel, which contained about 14 tonnes of sediment. Some of the discrepancy between the slide and cone volumes is accounted for by transport of sediment as a 'slug' in the main channel, but the majority of material remained in the tributary gully. This example showed that in excess of 14 tonnes or 22% of the slide volume passed into the tributary gully at the time of failure, suggesting a low sediment delivery ratio and thus storage of sediment in the system.

Caine and Swanson (1989) also consider the sediment delivery ratios between hillslopes and channels, expressed as the ratio of inorganic sediment exported from the basin to the mass transferred to the channel from the hillslopes. For watershed 10 the ratio is 0.77, and 0.11 for Martinelli when the dominant solute load is removed. The implication of these ratios is that this Rocky Mountain system is an aggrading system, as only 11% of the particulate load received by the stream is exported out. In contrast the Cascades basin has a near balanced sediment budget, retaining a much smaller percentage of received hillslope sediment in the channel. However, over a longer time scale watershed 10 must show a budget deficit to account for observed channel lowering.

2.4.2 Palaeohydrology

Gregory (1983) considers in some detail what palaeohydrology constitutes and indeed how the subject has developed. One of the earliest palaeohydrological studies was conducted by Leopold and Miller (1954) who studied the post glacial chronology for alluvial valleys in Wyoming. However, Gregory (1983) and Williams (1988) consider it was Schumm (1965, p783) that pioneered the development of palaeohydrology, providing a useful definition of palaeohydrology:

"The science of hydrology encompasses the behaviour of water as it occurs in the atmosphere, on the surface of the ground and underground. Palaeohydrology treats these phenomena, but it has reference to the past...The term palaeohydrology will be restricted to that portion of the hydrologic cycle that involves the movement of water

over the surface of the earth, because runoff and its sediment load are of major importance in determining the nonglacial erosional and depositional features of the Quaternary."

Following Schumm (1965), many broadly similar definitions have been proposed by Gregory and Walling (1973); Cheetham (1976); Lewin (1977). More recent definitions offered by Costa (1987), Williams (1988) and Jarrett (1991) whilst still similar to the original precept of Schumm (1965), focus on fluvial palaeohydrology, which Williams (1988, p321) considers the study of former rivers and their channels. This includes aspects such palaeo-channel dimensions, channel slope, meander geometry (for example: Schumm, 1968, 1969, 1972; Hedman and Osterkamp, 1982; Kochel and Baker, 1982; Bridge, 1985; Williams, 1988); and palaeo-flow characteristics such as velocity and discharge (for example: Kochel *et al.*, 1982; Costa, 1983; Williams, 1983; Maizels, 1983; Carling and Glaister, 1987; McEwen and Werritty, 1988; Williams, 1988; Kochel and Baker, 1988; Jarrett, 1991; Clarke, 1996).

One application of palaeohydrology in the study of upland/ mountain drainage basins is the ability to reconstruct palaeoflood characteristics, using a combination of geomorphological evidence and hydraulic relationships (see Chapter 7 for specific details), in the absence of flow records. Studies conducted by Mears (1979); Bradley and Mears (1980); Costa (1983); Carling (1986); Carling and Glaister (1987); McEwen and Werritty (1988); De Jong (1992); Waythomas and Jarrett (1994); and, Clarke (1996) are examples of such approaches. These studies can to some extent be categorised according to their overall aim, which include: to place a given flood in the context of long-term landscape development; to reconstruct the multi-flood history of an individual basin; and finally to make estimates of, or comparisons to, the probable maximum flood.

Carling (1986) in a study of the Noon Hill flash floods of July 1983 (North Pennines) and McEwen and Werritty (1988) in a study of the Allt Mor torrent flood of August 1978 (Cairngorms-Scotland), consider these storms as high magnitude-low frequency events. In the case of the Allt Mor catchment the August 1978 flood was generated by an intense rainfall event peaking at 33.5 mm h^{-1}, which in the UK has a recurrence interval of around 50 years (McEwen and Werritty, 1988). In the absence of gauged flow records, discharge was reconstructed using the slope-area method and the Darcy-Weisbach friction factor at various points in the catchment. This yielded a maximum discharge range of 67-81 $m^3 s^{-1}$. By using a Shields entrainment function it was deduced that the flood was competent to transport clasts larger than the D_{84} value of the bed material. On the basis of rainfall records the event was considered to have a recurrence interval of between 50 and 100 years. The impacts of this flood were most noticeable in the lower reaches. However, the general persistence of the pre-flood planform and larger channel features leads to the suggestion that larger floods prior to the 1978 event had been more formative, which implies that earlier floods would have had to be of higher discharge and flow competence. It is concluded that the Allt Mor basin is only sensitive to high magnitude-low frequency events. Detail of past floods can be determined when palaeohydrology is used to reconstruct multiple flood histories. Waythomas and Jarrett (1994) conduct a study of Arthurs Rock Gulch, in the Colorado Front Range. Using boulder and slackwater deposits, and erosional terraces, evidence of five historical dated floods in the last 40,000 years was obtained.

Estimates of the probable maximum flood are also commonly made (Carling and Glaister, 1987; Carling, 1997; and Clarke, 1996). Carling and Glaister (1987) reconstructed the Glenridding Beck dam break flood of October, 1927 (English Lake District), using the U.S. National Weather Service model 'DAMBRK' as described by Fread (1984). Input components included the tarn basin and moraine breach geometry; downstream variations in channel cross-section; expected stage heights from trimlines and boulder berm elevations to constrain the hydrograph; and coefficients of roughness, expansion and contraction. Using model hydrographs, after the removal of the baseflow components, flood discharges of between 90 - 100 $m^3 s^{-1}$ were predicted at Glenridding village. It was concluded that this discharge was not exceptional and could be exceeded by natural flood events, given that it is less than half the probable maximum flood calculated using the Flood Studies Report method (NERC, 1975).

The foregoing considerations of sediment budgets and palaeohydrology have shown that these techniques allow spatial and temporal variations in process activity to be determined, and the impact of high magnitude-low frequency events to be calculated. Hence the application of both techniques allows detailed contemporary process understanding to be placed in a wider temporal context. Such a framework will provide a more comprehensive approach to the investigation of torrent erosion, which to date has been dominated by investigation of channel processes over short time periods.

2.5 Summary

This chapter has undertaken three tasks. Firstly, it has provided a background to the characteristics of mountain catchments and their geomorphological process activity. Secondly, it outlines the sediment-water flow spectrum, and proposes a morphological continuum of channel and hillslope forms. An important member of this continuum is torrents, which provide linkage between higher and lower elevations for sediment transport and water flow. A consideration of the current state of torrent research indicates the incomplete understanding of sediment supply dynamics, thereby providing the basis for the research aims and objectives contained in chapter 1. The third part of this chapter considers the two main techniques used in the Lake District investigations, namely sediment budgeting and palaeohydrology. The next chapter builds on this background, by considering the study area.

CHAPTER 3: BACKGROUND, STUDY AREA, AND SCOPE OF THE INVESTIGATION

3.0 Scope of chapter

This chapter describes characteristics of the English Lake District, which are pertinent to the study sites considered in this research project. Section 3.1 provides a general description of the Lake District and gives details of the National Park and the general landscape; which has been fashioned by geology, geomorphological processes, and vegetation change. Background is given to the contemporary environment. This includes details of climate, drainage, soils, vegetation, land use and management strategies.

The overall methodology used to investigate torrent characteristics in Lake District mountain catchments is a 'nested scale approach'. Section 3.2 defines this approach, outlining details of the case study sites (Iron Crag and Raise Beck), and discusses the background to the regional study areas. Section 3.3 summarises these main landscape characteristics and draws contrasts between the Skiddaw and Helvellyn massif regions, and the Iron Crag and Raise Beck sites. Finally, an outline is given of where in the thesis further details of these sites can be found.

3.1 General description of the English Lake District

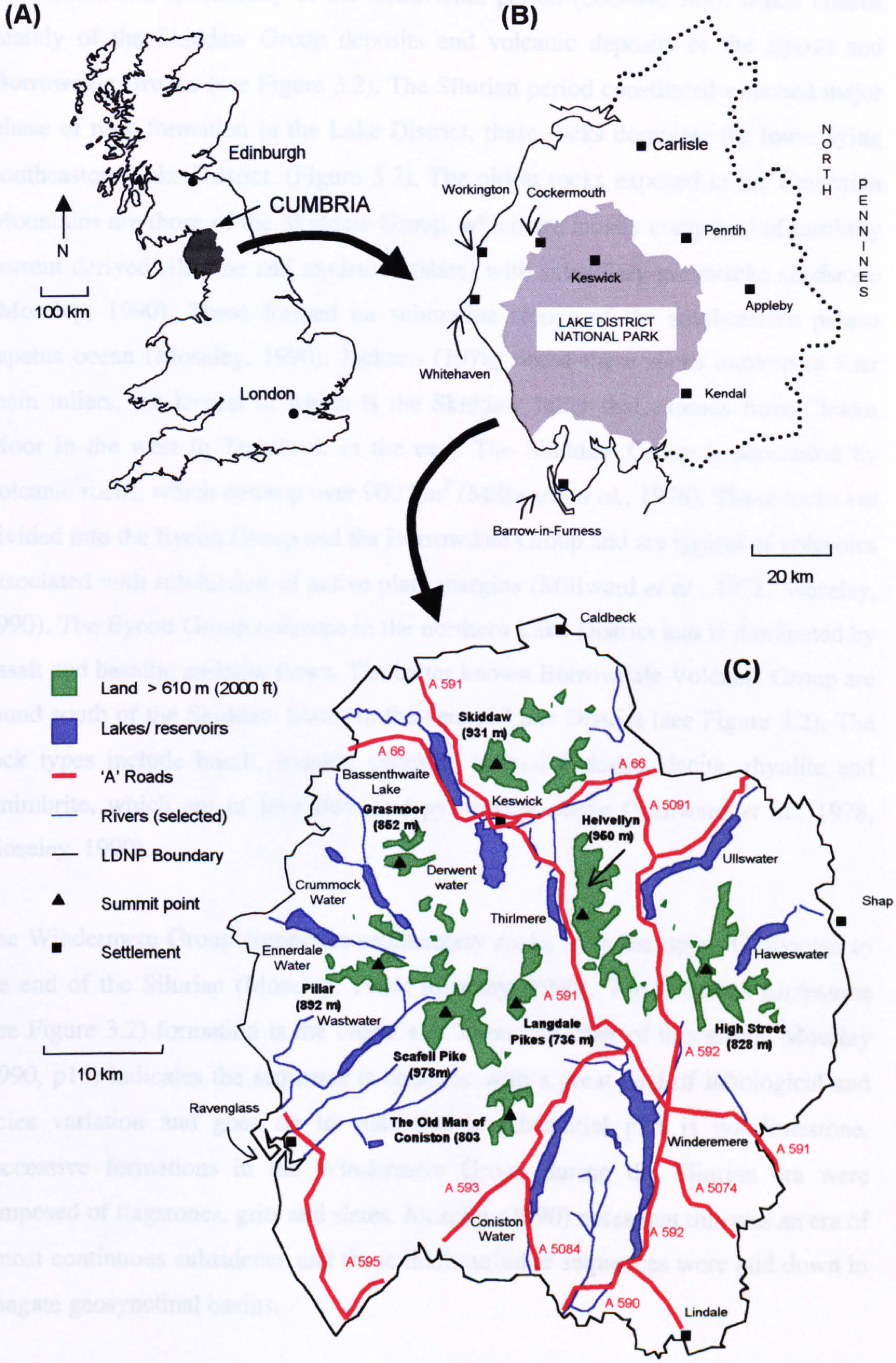
The Lake District is one of 11 National Parks in England and Wales, it was established on the 15th August 1951 (LDNPA, 2000a) shortly after the Peak District National Park (the first National Park). The Lake District is situated in North West England. The National Park has an area of 2279 km^2 (Tarn and Wilson, 1994) and encloses approximately one third of the County of Cumbria (LDNPA, 2000a). As such it is the largest upland National Park in England and Wales, accounting for 1.51% of the land area of England and Wales (Fielding and Haworth, 1999). It extends from Caldbeck in the north to Lindale in the south, from Ravenglass in the west to Shap in the east (LDNPA, 2000a) (Figure 3.1). Most of the Lake District lies above 250 m O.D., with the highest point in the Lake District (and England) being Scafell Pike (978 m O.D., NY 215 072). Areas of sustained higher relief (greater than 610 m O.D.) include ground around Skiddaw (931 m O.D., NY 261 291); Helvellyn (950 m O.D., NY 341 151); High Street (828 m O.D., NY 440 110); The Old Man of Coniston (803 m O.D., SD 273 978); Scafell Pike/ Langdale Pikes/ Pillar (978 m O.D. to 736 m O.D.) and Grasmoor (852 m O.D., NY 174 204).

The Lake District is characterised by a mixed topography, which the Lake District National Park Management Plan (LDNPA, 1999) categorises into a number of types. These include the fells, valleys, and the coast. Lakes, tarns and rivers, forests and woodland are also considered though they are not strictly topographic categories. Of relevance to this study are the fells, specifically the high fells, the landscape characteristics of which are outlined by Countryside Character Programme (1996). It is stated:

"The wild, exposed and open high fells are characterised by rough grassland, dwarf shrub heaths, peatlands, bracken and areas of rock outcrop and screes. In the north and west, the Skiddaw slates have been eroded to form steep sided round humps such as Blencathra, Skiddaw, Bowscale, Carrick, Uldale and the Caldbeck Fells. Whilst in the south, the harder Borrowdale Volcanics result in the rugged scenery of exposed crags, ridges and vertical rock exposures characteristic of the Helvellyn, Scafell and Langdale ranges. The presence of rock basins, aretes, ghylls, tarns and waterfalls and fast flowing streams form distinctive elements in the landscape."

The present landscape of the Lake District is a product of many millions of years evolution. Pearsall and Pennington (1973, p22) state *"Field studies are the basis of any consideration of the development and history of the landscape. A landscape is the product of geology and history."* Therefore it is helpful to outline the geological and geomorphological history of the Lake District (e.g. Macan, 1970; Smith, 1977; Tarn and Wilson, 1994; Countryside Character Programme, 1996; Boardman, 1996; Ratcliffe, 1997a; LDNPA, 2000b) and discuss the influences of climate, drainage, vegetation, land use, and soil characteristics.

Figure 3.1: Lake District location maps. (A) Location of Cumbria in the UK, (B) Boundaries of the Lake District National Park within Cumbria, (C) Detailed map of the Lake District showing land over 610 m O.D.

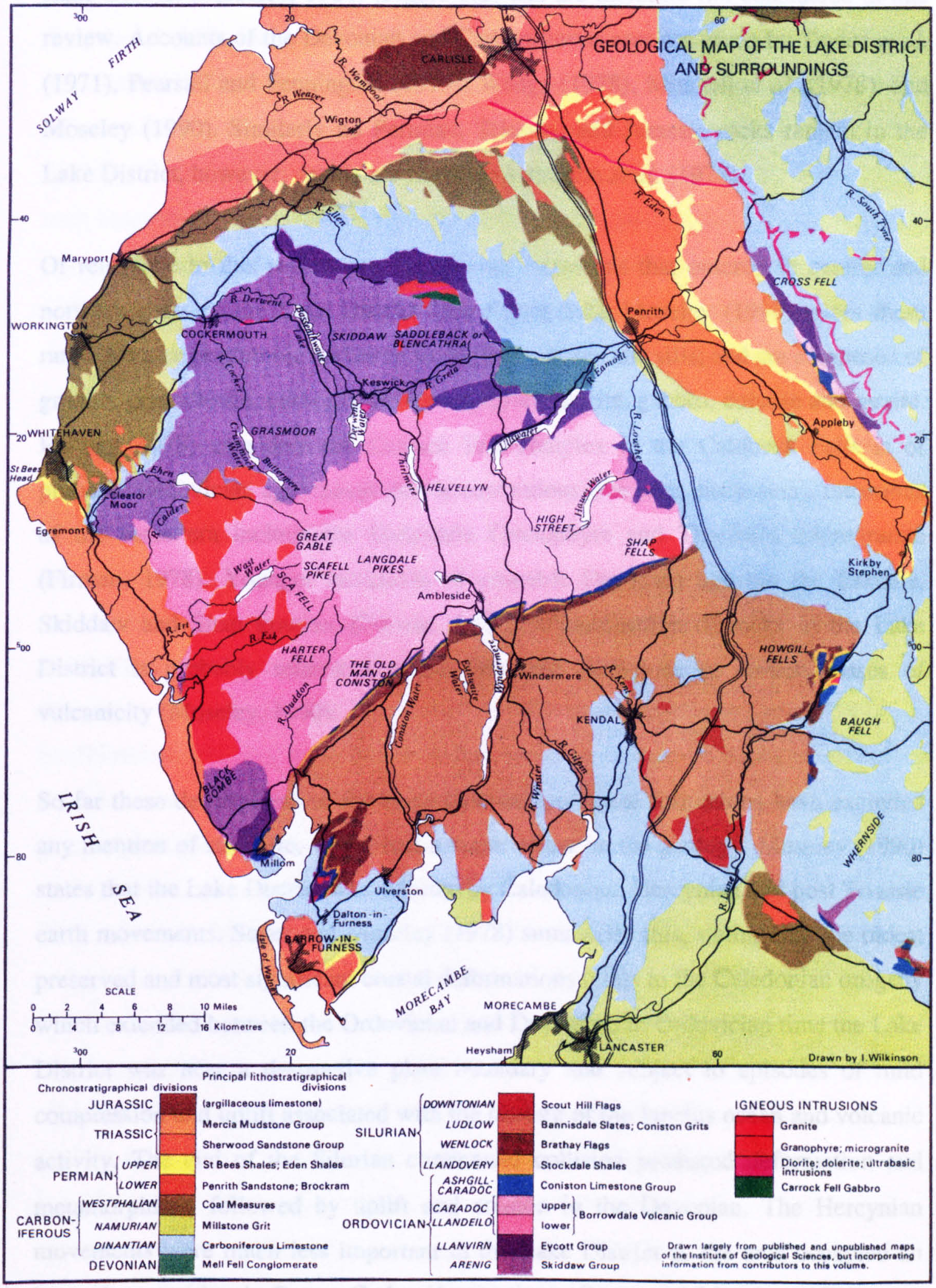


3.1.1 Geology

The solid geology of the Lake District is dominated by rocks from the Lower Palaeozoic era, specifically of the Ordovician period (500-440 Ma), which consist mainly of the Skiddaw Group deposits and volcanic deposits of the Eycott and Borrowdale Groups (see Figure 3.2). The Silurian period constituted a second major phase of rock formation in the Lake District, these rocks dominate the lower lying southeastern Lake District. (Figure 3.2). The oldest rocks exposed in the Cumbrian Mountains are those of the Skiddaw Group, which are mostly composed of turbidity current derived siltstone and mudstone (slate) with subsidiary greywacke sandstone (Moseley, 1990). These formed on submarine slopes of the southeastern palaeo Iapetus ocean (Moseley, 1990). Jackson (1978) noted these rocks outcrop in four main inliers, the largest of which is the Skiddaw Inlier that extends from Cleator Moor in the west to Troutbeck in the east. The Skiddaw Group is succeeded by volcanic rocks, which outcrop over 900 km^2 (Millward *et al.*, 1978). These rocks are divided into the Eycott Group and the Borrowdale Group and are typical of volcanics associated with subduction of active plate margins (Millward *et al.*, 1978, Moseley, 1990). The Eycott Group outcrops in the northern Lake District and is dominated by basalt and basaltic andesite flows. The better known Borrowdale Volcanic Group are found south of the Skiddaw Slates in the central Lake District (see Figure 3.2). The rock types include basalt, basaltic andesite, normal andesite, dacite, rhyolite and ignimbrite, which are of lava flow and pyroclastic origin (Millward *et al.*, 1978, Moseley, 1990).

The Windermere Group comprises sedimentary rocks from the upper Ordivician to the end of the Silurian (Moseley, 1984; Moseley, 1990). The Coniston Limestone (see Figure 3.2) formation is the oldest and lowest member of this group. Moseley (1990, p16) indicates the sequence is complex with a great deal of lithological and facies variation and goes on to state that a substantial part is not limestone. Successive formations in the Windermere Group during the Silurian era were composed of flagstones, grits and slates. Moseley (1990) notes that this was an era of almost continuous subsidence and these thick turbidite sequences were laid down in elongate geosynclinal basins.

Figure 3.2: **Geological map of the Lake District**
(Reproduced with permission of the Yorkshire Geological Society, Moseley, 1978).



After the Silurian further significant rock formation occurred in the Devonian and Carboniferous periods (Moseley, 1990). These rocks outcrop on the periphery of the Lake District (Moseley, 1984) (Figure 3.2) and are therefore not considered in this review. Accounts of the Devonian and Carboniferous eras are given by Taylor *et al.* (1971), Pearsall and Pennington (1973); Wadge (1978); Mitchell *et al.* (1978), and Moseley (1990). Similarly no Permian, Triassic, and Jurassic rocks remain in the Lake District, however, details are found in Arthurton *et al.* (1978).

Of relevance to this review are the igneous intrusions that outcrop in central and northern parts of the Lake District (see Figure 3.2). Moseley (1990) states these range from large plutonic bodies to small plugs, dykes and sills; and are composed of granite, granodiorite, microgranite (granophyre), diorite, gabbro, dolerite and picrite. Firman (1978) considers the Carrock Fell complex in the Caldbeck Fells is of probable Ordovician age, though this is contentious (see later discussion). Intrusions of the same era include the Ennerdale Granophyre and Threlkeld microgranite (Firman, 1978). Younger intrusions of probable Devonian age are the Eskdale, Skiddaw and Shap granites (Firman, 1978). Mineralisation of rocks in the Lake District is probably related to these Devonian intrusions or earlier phases of vulcanicity (Moseley, 1990).

So far these descriptions of the Lake District geological formations have excluded any mention of structure, which had a major effect on the geology. Moseley (1990) states that the Lake District was affected by Caledonian, Hercynian and post Triassic earth movements. Soper and Moseley (1978) summarise this, stating that the oldest preserved and most significant crustal deformations relate to the Caledonian orogeny which extended between the Ordovician and Devonian. In Ordovician time the Lake District was near a destructive plate boundary and subject to episodes of mild compression and uplift associated with the closing of the Iapetus ocean and volcanic activity. The end of the Silurian continental collision produced deformation and metamorphism, followed by uplift and erosion in the Devonian. The Hercynian movements were much less important in the Lake District as the area occupied an intra-plate position in Permo-Carboniferous times. Soper and Moseley (1978) state that Hercynian activity reactivated older Caledonian structures. In post Triassic (later Mesozoic and Tertiary) times, northern Britain was under mild tension with the constructive widening of the Atlantic Ocean resulting in normal faulting and the gentle doming of the Lake District.

Sedgwick (1842), Smith (1959, 1977), Lunn (1970), Pearsall and Pennington (1973), Boardman (1996), Countryside Character Programme (1996), and LDNPA (2000b) all consider the implications of the geology on the Lake District Landscape. The Skiddaw Slates give rise to smooth conical shaped slopes, generally unbroken by rock outcrops. Conversely the variety of the Borrowdale Volcanic Group results in rugged stepped topography, where resistant beds stand out as steep cliffs. Boardman (1996) considers the Silurian rocks in the southern Lake District to be less resistant than the Borrowdale Volcanics and more varied than the Skiddaw Group, and as a consequence display smaller scale relief. Boardman (1996, p10) states that only three of the major lakes (Thirlmere, Wast Water, Haweswater) are formed in the Borrowdale Volcanic outcrop; the majority are in softer rocks to the north and south. Finally the often quoted radial drainage pattern of the Lake District is considered to be the superimposition of a drainage network onto old hard rocks of a pattern developed on the Post Triassic rocks of the largely stripped Lake district dome (Mill, 1895; Marr, 1889, 1916; Soper and Moseley, 1978; Boardman, 1996, Countryside Character Programme, 1996, Evans, 1997b) (see later discussion). Further modifications resulting in the current Lake District landscape are largely attributed to process activity during the Quaternary era (Boardman, 1992). This geomorphological history is now considered.

3.1.2 Geomorphological history

Boardman (1992, 1996) states that the Lake District landscape is widely considered to be the product of surface processes operating during the Quaternary, and shows classic evidence of glaciation as suggested by Linton (1957) and Boulton *et al.* (1977). King (1976, p102) and Moseley (1978) consider the glacial erosion of the Lake District to be a product of the Devensian Late glacial.

Boardman (1992) states that the Late Quaternary can de divided into three distinct environments: glacial; periglacial / restricted glaciation; and interglacial / temperate. Each have characteristic types of process activity (see Table 3.1). Figure 3.3

proposes a climate curve for the Late Quaternary applied in the Lake District. Boardman (1991, 1992) considers the deep valleys of the Lake District not to be the product of the Dimlington Stadial (26-13 ka BP) when an extensive ice sheet existed, but earlier glaciation. An example used in support of this argument is the apparent lack of erosion in the Vale of Threlkeld (NY 326 254) (1-2 m of erosion), and the corresponding preservation of a pre-Devensian till at Mosedale Beck (NY 355 240). Earlier glaciations are considered responsible for the deepening of Vale of Threlkeld; a drainage diversion of the River Glenderamackin (NY 290 246) requiring a 100 m overdeepening; and the truncation of the southerly spurs of Blencathra (north side of the Vale of Threlkeld, NY 320 263). It is proposed that the lack of erosion suggests that Lake District valleys were already adjusted to the passage of ice. The alternative, that valleys were occupied by cold based/ non erosive ice, is discounted because of the existence of drumlins which indicate basal sliding and therefore a warm based Late Devensian glacier. However, Evans (1997b) points out that erosion in the area of Mosedale Beck was probably unnecessary as a 2 km increase in valley width after the Clough Head/ Blencathra constriction allowed north easterly flowing ice to spill out. Furthermore Evans (1997b) argues that the preservation of pre-Devensian deposits at one location does not preclude Devensian erosion elsewhere.

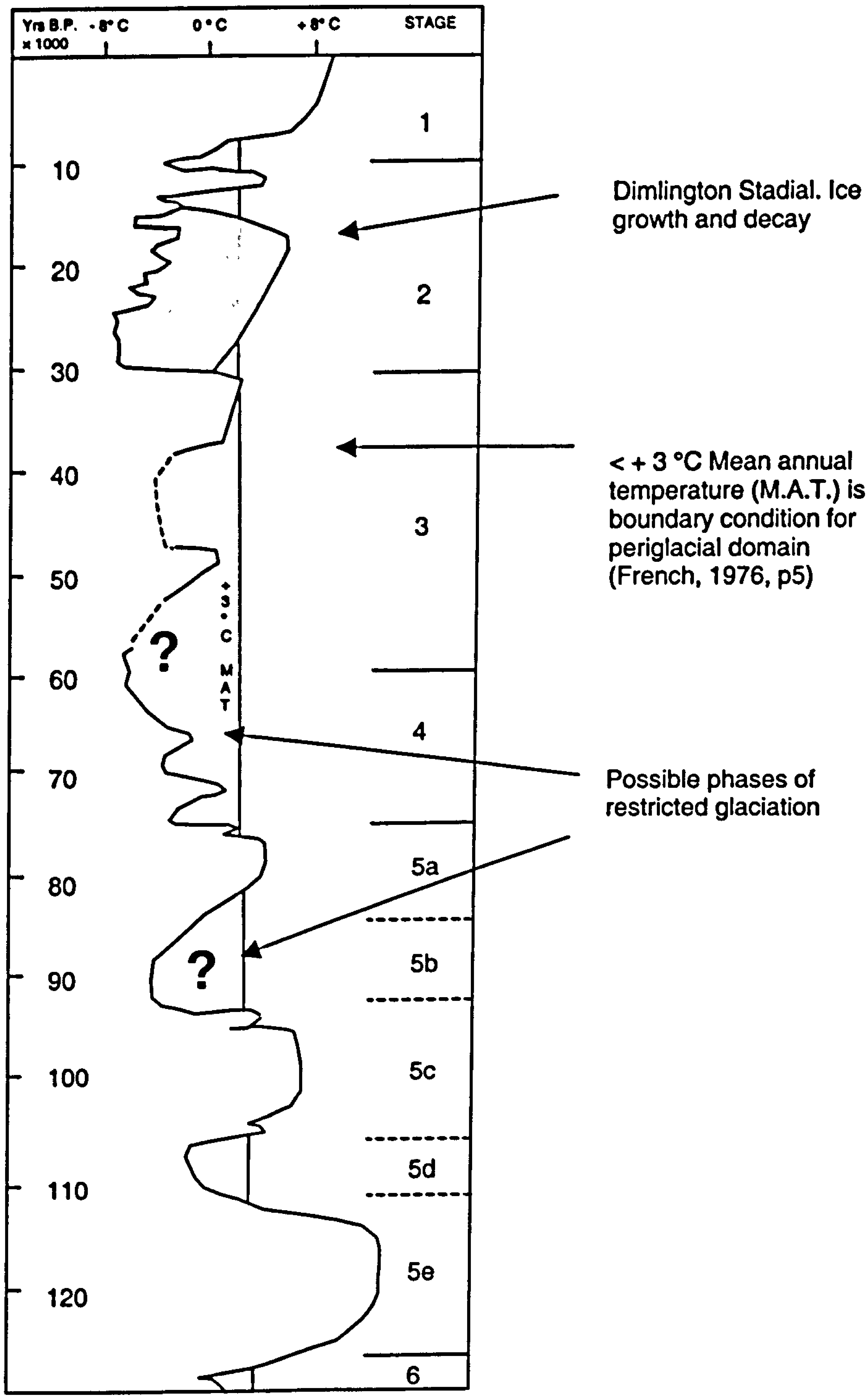
Boardman (1992) also suggests that restricted glaciation (small cirque and valley glaciers) was the norm for long periods of the Quaternary in the Lake District. This is based on the evidence of sustained cold non-ice sheet phases of climate (Figure 3.3), especially between 75, 000 and 30,000 BP. Secondly, a recent analogue for this type of glaciation, is the Loch Lomond Stadial (11 –10 ka BP). Third, the presence of many cirques (Sissons, 1980; Evans and Cox, 1995; Evans, 1997b; Wilson and Clark, 1999) implies regional glaciation to be rare and ineffective. It is generally agreed that many phases of restricted glaciation would have been required to form the Lake District cirques. Clough (1977) shows the last glaciers to occupy Lake District cirques had a different orientation to that of the main cirque form. Evans (1997b) also states that cirques developed over a series of local glaciations during the Quaternary.

Table 3.1: Quaternary environments in the Lake District, based on subdivisions of the glacial/ interglacial cycle (128 ka to 10 ka BP) shown as Figure 3.3 (Table from Boardman, 1992)

Environment	Dominant Processes	Duration of Time (%)
Glacial (ice sheet)	Erosion and transport including meltwater effects	13
Periglacial ± restricted glaciation (<+ 3 °C M.A.T.)	Frost weathering, cryoturbation, solifluction, fluvial erosion and transport	58
Interglacial and Temperate (> 3° C M.A.T.)	Weathering and soil formation	29

Boardman (1992) argues that periglacial processes have operated in the Lake District for prolonged periods of time, especially in conjunction with restricted periods of glaciation. Periglacial processes are considered to have had a considerable role in landscape modification. Many slopes have thick covers of frost shattered debris, younger than the Dimlington Stadial, and are believed to have formed in the Loch Lomond Stadial under cold and wet conditions. Much of the material produced traveled short distances covering hillslopes, whilst material reaching river channels was transported to other storage sites such as alluvial fans, floodplains and lake basins. Boardman (1992) estimates the rate of surface lowering due to frost weathering to be about 1 mm a^{-1}, whereas glacial erosion of bedrock is below 0.5 mm a^{-1}. However the overall rate of erosion during glacial phases will be greater, as measures of glacial erosion often include material supplied by periglacial and slope failure processes. The duration of periglacial conditions (Table 3.1) may have also persisted for four times longer than glacial conditions. However, it is noted that the snowier conditions of the Loch Lomond Stadial were climatically atypical, and therefore the rates of geomorphic activity associated with this were likely to be greater than those occurring in earlier colder/ drier periods of restricted glaciation. Boardman (1992) nevertheless concludes that combined frost weathering and snowmelt provided the most effective group of processes producing landscape change in the Lake District during the Quaternary.

Figure 3.3: Tentative climate curve for the Late Quaternary in the Lake District (from Boardman, 1992)



Evans (1997b) states the rounded northern fells show little evidence of glacial erosion and are more likely the products of periglacial and fluvial erosion. More recently Wilson and Clark (1999) suggest the existence of four Loch Lomond Stadial glaciers/ snowbeds around Knott in the northern fells (NY297 330), which add to the small number of Loch Lomond features already identified in the northern fells (Evans, 1997b; Boardman 1996). Both papers support Boardman's (1992) model of restricted glaciation and periglacial activity. However, Evans (1997b) goes on to state that rates of glacial erosion would be greater in the central fells, which is contrary to the argument advanced by Boardman (1992).

In light of the foregoing discussions it can be concluded that the widely held belief that the Lake District only displays evidence of glacial activity during the Dimlington and Loch Lomond Stadials is too simplistic. Whilst ice sheet and restrictive glaciation occurred, the rates of glacial process activity during these time periods is insufficient to fully explain the form of the Lake District landscape. Boardman (1992) notes that periglacial activity was significant, especially in the northern fells which are primarily composed of frost susceptible Skiddaw slates. It is likely that glacially eroded forms, especially cirques, reflect the impact of many phases of restricted glaciation.

3.1.3 Vegetation history

The vegetation history of the Cumbrian uplands has been strongly influenced by both climate and early human settlement. Pennington (1997) provides a review of the Cumbrian vegetational chronology from the Lateglacial period through to the present. A summary account of this is repeated here. In the Lateglacial period few plants are likely to have existed, and during the initial phases of deglaciation the area would have resembled a polar desert. Later in deglaciation, plants would have migrated from southern England, forming pioneer cold tolerant communities. After 14000 BP the pioneer vegetation became more 'luxuriant', there was increased pollen deposition, and succession to grasslands. By 13000 BP a milder climate enabled the spread of woody vegetation forming open woodlands composed of *Juniperus* and *Betula*, supplemented with grasses. This period is referred to as the Windermere Interstadial (Coope and Pennington, 1977). The Interstadial ended with the onset of the cooler Loch Lomond Stadial (c. 11000 BP), which caused the formation of small glaciers in Cumbria. Together with periglacial processes, soil surfaces were disturbed leading to a breakdown of the previous vegetation communities. Plants existing in this colder environment were those tolerant to disturbance, and trees disappeared for approximately 1000 years. The onset of the Holocene (10000 BP) allowed *Juniperus* to again become dominant, which led to a closed canopy of *Betula* woodland (though this was probably more open at elevations in excess of 500m O.D.). *Corlyus* spread starting about 9700 BP and eventually surpassing the *Betula*. *Quercus* and *Ulmus* spread from the south later. Between 7500 to 5000 BP vegetation was dominantly arboreal, composed of *Quercus*, *Ulmus*, *Corlyus*, *Alnus* and *Betula*. Pollen diagrams illustrate variations in these arboreal communities that existed due to altitudinal and edaphic gradients.

During the Mesolithic in Britain (14,000 to 5500 BP) hunter-gatherer cultures commonly carried out burning of upland vegetation. However, in Cumbria the evidence for this is limited. It was not until the Neolithic (5500 to 4500 BP) that human communities started to really affect the upland vegetation in Cumbria. In the proximity of Neolithic sites an expansion of grasses suggests some deforestation and grazing. Such evidence has been used to suggest that an Iron Age (possibly Neolithic) hill fort existed at the top of Carrock Fell (LDNPA, 1997). Vegetation clearances in this area of Cumbria could relate to this settlement. The decline of woodlands was fragmentary as some localities survived for several thousand more years. Despite local variations the main regional clearance was completed by 1000 BP in association with Norse settlements, and later Monastic land use. At first *Calluna*-dominated heath replaced the lost woodland, but this gave way to grasslands associated with upland sheep farming (Pennington, 1997; Ratcliffe and Halliday, 1997). Therefore vegetational changes in the last 5000 years have been both climatically and anthropogenically driven.

3.1.4 Contemporary climate

Manley (1973) states that the climate of the Lake District is that of a small group of mountains and valleys often subject to westerly airmasses. A well-established and distinctive feature of the Lake District climate is rainfall variability (Miller 1849;

Huddleston, 1935; Macan, 1970; Bendelow, 1984; Tarn and Wilson, 1994; Ratcliffe, 1997b). Manley (1973) states that the general pattern of rainfall increases from a low at the coast to a maximum in the central fells and thereafter declines in a north and east direction. Figure 3.4 shows the general pattern of average annual rainfall between 1916 and 1950. A secondary peak occurs on the Skiddaw massif. Manley (1973) quotes examples of variations: compared with Low Furness, five times as much rain falls at Sprinkling Tarn beneath Great End (NY 2283 0905, 600 m O.D., where the average annual totals 185 inches (4699 mm)). The valley heads of Eskdale, Langdale and Borrowdale intercept in excess of 150 inches (3810 mm) of rain a year. Manley (1973) explains these high rainfalls as a result of orographic forcing and the convergence of surface air streams along the radial Lake District valleys. As a result of this prolonged wetness Bendelow (1984) concludes that the land is at field capacity for long periods, up to 300 days for most areas. Consequently the summer maximum soil moisture deficit is low, generally less than 50 mm.

Although, the Lake District lies between latitude 54° and 55° N its winters are particularly mild, and its summers are relatively cool (LDNPA, 2001; Tufnell, 1997). This is a function of the warming influence of the North Atlantic drift and the passage of low pressure systems. At a local level, Tufnell (1997) shows monthly temperatures at Grizedale (south Lake District) to be not too dissimilar to those recorded elsewhere in north west England (Table 3.2). Although Grizedale is consistently colder, both in maximum and minimum mean temperatures, than Morecambe (coastal) and Manchester Airport (inland). Tufnell (1997) states that Grizedale is typical of many Lake District valleys having a propensity for cold air drainage from the surrounding fells in all seasons. Tufnell (1997) continues that any assessment of temperatures should incorporate the fact that Cumbria is the only English region well endowed with lakes. Indeed, Manley (1973) compares maximum and minimum mean monthly temperatures at Appleby (sheltered inland valley location) and Keswick (station within a mile of two large lakes) for the period 1931-1960, making allowance for the altitudinal difference between the two stations (see Table 3.3). It is shown that larger lakes have a noticeable ameliorating effect,

Figure 3.4: Pattern of average annual rainfall in and around the Lake District 1916-1950, from Manley (1973)

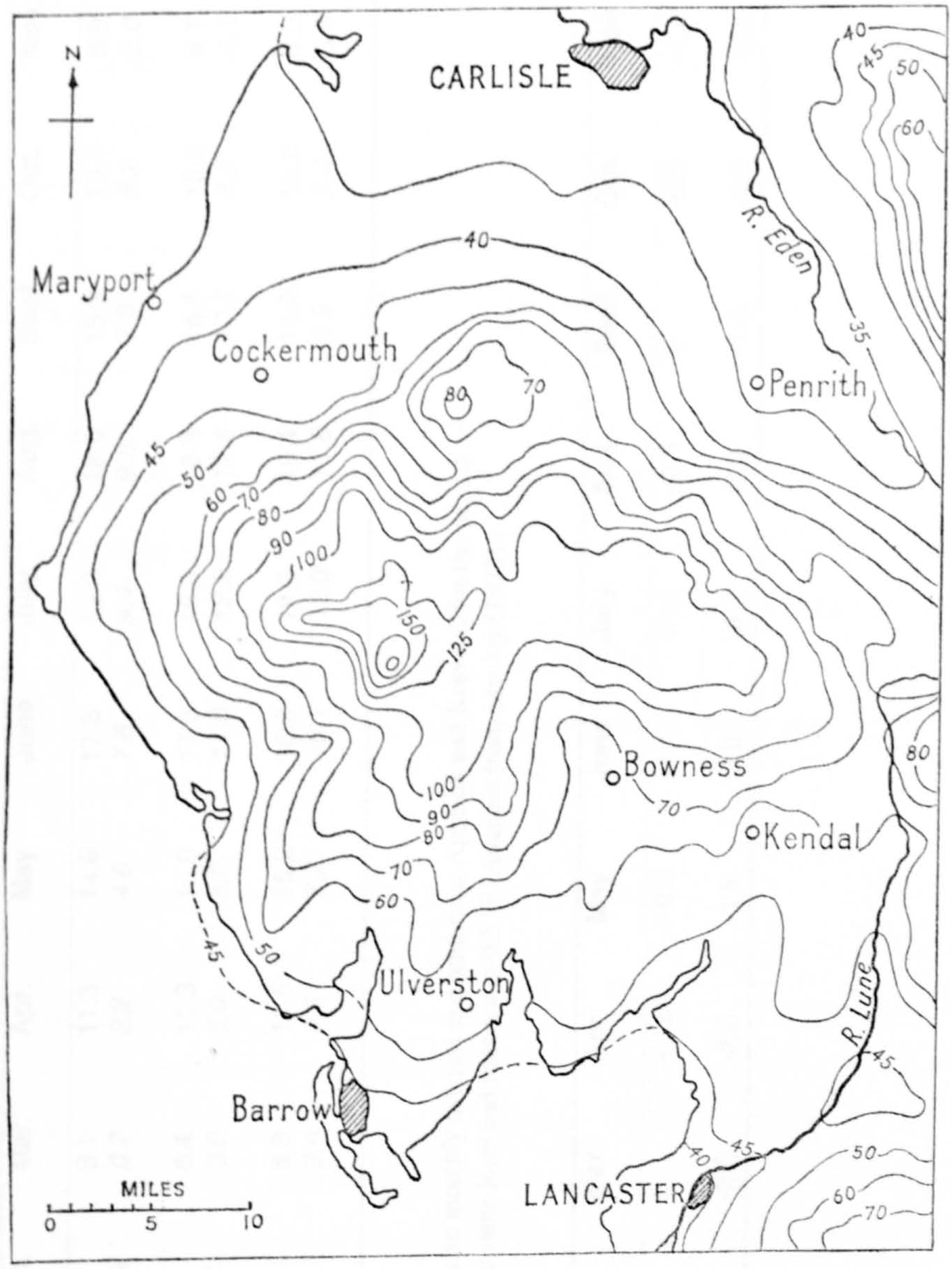


Table 3.2: Mean monthly maximum and *minimum* temperatures (°C) for the period 1961-90 (Adapted from Tufnell, 1997, Table 8.1).

Location	Altitude m ASL	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Grizedale	91	6.0	6.2	8.1	11.3	14.6	17.3	19.0	18.6	15.9	13.0	8.9	6.9
		-0.2	*-0.2*	*0.7*	*2.2*	*4.6*	*7.6*	*9.4*	*9.6*	*7.9*	*5.2*	*2.0*	*0.5*
Morecambe	7	6.1	6.5	8.4	11.3	15.0	17.6	19.0	18.8	16.6	13.6	9.1	7.1
		1.8	*1.8*	*3.0*	*5.0*	*8.0*	*11.0*	*12.9*	*12.8*	*10.7*	*8.2*	*4.4*	*2.5*
Manchester	75	6.3	6.5	8.8	11.5	15.2	18.2	19.6	19.4	16.9	13.6	9.0	7.1
Airport		*1.2*	*1.1*	*2.4*	*4.3*	*7.2*	*10.1*	*12.0*	*11.8*	*9.9*	*7.4*	*3.5*	*1.9*

Table 3.3: Difference between the mean monthly maxima and minima at Appleby and Keswick for the period 1931-1960: reduced to the same level and rounded to 0.5 °F (Adapted from Manley (1973).

Appleby Keswick Temperatures	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Maxima (°F)	-2.5	-2.5	0	+0.5	+0.5	+1.0	+1.0	+0.5	0	-0.5	-1.5	-2.0
Minima (°F)	-2.5	-2.5	-2.0	-2.0	-1.5	-2.0	-2.0	-2.0	-1.5	-2.5	-2.5	-2.5

Keswick is warmer except in the April- August maximum temperature, where the lakes provide a cooling rather than warming influence during the day.

However, upland and mountain temperatures do show marked contrasts with lower elevations. Ratcliffe (1997b) indicates that in general temperatures decrease with altitude at a lapse rate of 1° C per 150 m. In illustration of this Manley (1936) compares temperature records from Moorhouse (North Pennines) in the period 1932-1935 to four lowland stations in northern England, i.e. Newton Rigg (Penrith), Appleby, Houghall and Durham. It is found that the Moorhouse monthly maxima are 7 °F (4 °C) below those derived for the four stations. More recently Ratcliffe (1997b) provides examples of annual monthly temperatures for a selection of stations in Cumbria: Millom (9 m O.D.) 9.4° C, Keswick (76 m O.D.) 9.1 °C, Appleby (134 m O.D.) 7.8 °C, Moorhouse (556 m O.D.) 5.6 °C, and Great Dun Fell (847 m O.D.) 3.4 °C. In reference to North Pennine meteorological records (Moorhouse and Great Dun Fell), Manley (1973) indicates that the most noticeable feature in the uplands is a faster rate of fall in mean daily maxima, as a result of wind speed and a greater frequency of cloud cover.

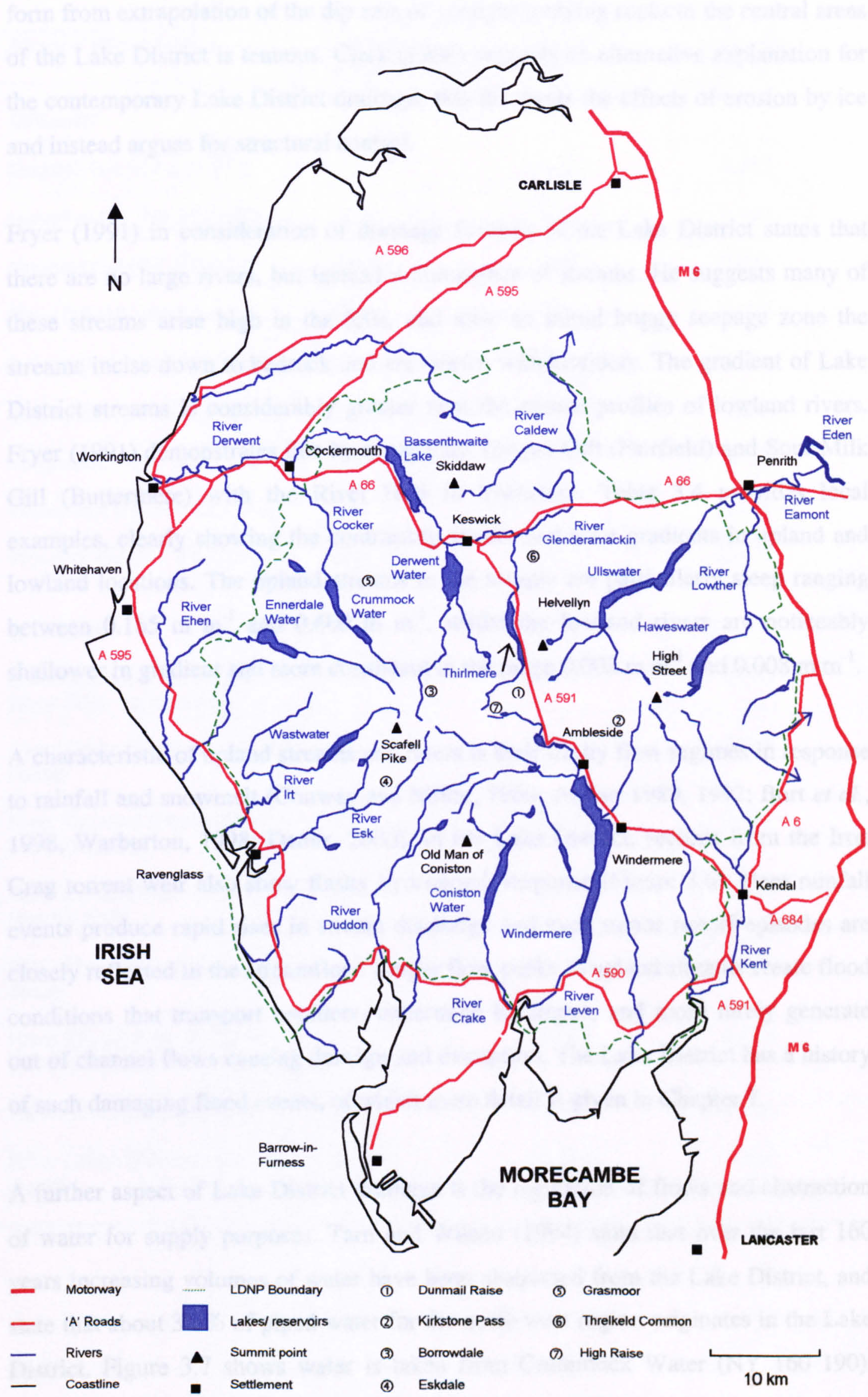
Manley (1973) following Manley (1942, 1943) notes that a very important feature of the high level climate is the greater frequency of temperature oscillations about freezing point. Hence a freeze-thaw climate prevails for long periods of every winter resulting in a high frequency of oscillations between cold rain, sleet or driving snow. With regard to snowfall and snowcover, Manley (1973) suggests that the valley floors around Keswick and Ambleside experience about 25 days in which snow falls primarily between December and March. On the Lake District summits in excess of 762 m (2500 ft) first snows are expected in mid October and might continue to the end of May. At this altitude snow cover may persist for 100 days. In exceptional winters this may rise to 160-170 days. Snow cover persists longer in the north and east, and less towards the west. The net effect of these weather patterns and meteorological variations is a harsh climate which the Bioclimatic map of England and Wales (Benedlow and Hartnup, 1980) classifies the central Lake District as 'arctic', 'very wet' and 'very exposed to winds'.

3.1.5 Surface drainage

Figure 3.5 illustrates the principal rivers and lakes in the Lake District. In the north drainage is dominated by the River Derwent and its tributaries, collecting runoff from the west and south of the Skiddaw massif and Threlkeld Common; the Thirlmere Reservoir catchment which includes the west side of the Helvellyn massif north of Dunmail Raise; around Borrowdale; and the north western fells of Robinson and Grasmoor. In terms of the latter, the easterly drainage enters Bassenthwaite Lake, but the westerly drainage (tributaries of the River Cocker) do not join the River Derwent until Cockermouth, outside the National Park. The River Caldew is the other dominant drainage in the northern Lake District, collecting water from the centre and north of the Skiddaw massif. The drainage of the eastern Lake District (east of the Helvellyn massif to Kirkstone Pass, north of Ullswater, High Street area, and Haweswater) is the catchment for the River Eamont and River Lowther, which join the River Eden 5 km east of Penrith. The waters of the southern Lake District discharge into Morecambe Bay, via the Rivers Leven, Crake and Duddon. The River Leven exits from Windermere, which has a catchment including the south of the Helvellyn massif and the Langdale area. The River Crake draining Coniston Water has a smaller catchment area originating in the Coniston Fells. In the south-west drainage discharges into the Irish Sea at Ravenglass, from the Rivers Esk, Mite and Irt. The River Esk's catchment is Eskdale, and the Upper Eskdale Basin that is surrounded by the high fells of Scafell, Scafell Pike, Bowfell and Crinkle Crags. The River Irt exits from Wastwater having a catchment beginning in the Wasdale Head area, with the southern slopes the fells Pillar, Great Gable and the west face of Scafell.

Figure 3.5 tends to suggest that the main rivers of the Lake District radiate out from a central area. This long held hypothesis of radial drainage (as outlined earlier) is investigated by Clark (1988). He questions the validity of this 'orthodox account' of the Lake District relief. Several arguments are presented, firstly, valley heads fail to diverge from a relatively small central area, but instead predominately extend along an east-west watershed over an area of 20 km north to south. Furthermore, the locations of the highest ground, i.e. Scafell Pike, Helvellyn, and Skiddaw, are of variable height and up to 20 km from High Raise (NY 281 095, 762 m O.D.) which

Figure 3.5: **Drainage in and around the Lake District National Park.**



is the centre of radiation proposed by Mill (1895). Secondly, reconstructing a dome form from extrapolation of the dip axis of younger outlying rocks to the central areas of the Lake District is tenuous. Clark (1988) suggests an alternative explanation for the contemporary Lake District drainage, this discounts the effects of erosion by ice and instead argues for structural control.

Fryer (1991) in consideration of drainage features of the Lake District states that there are no large rivers, but instead a dominance of streams. He suggests many of these streams arise high in the fells, and after an initial boggy seepage zone the streams incise down to bedrock and are strewn with boulders. The gradient of Lake District streams is considerably greater than the stream profiles of lowland rivers. Fryer (1991) demonstrates this by comparing Tongue Gill (Fairfield) and Sour Milk Gill (Buttermere) with the River Hull in Yorkshire. Table 3.4 provides local examples, clearly showing the contrasting stream and river gradients in upland and lowland locations. The upland streams in the sample are particularly steep ranging between 0.165 m m^{-1} and 0.600 m m^{-1}, whilst the lowland rivers are noticeably shallower in gradient and more consistent in the range 0.002 m m^{-1} and 0.008 m m^{-1}.

A characteristic of upland streams and rivers is their flashy flow regimes in response to rainfall and snowmelt (Conway and Millar, 1960; Archer 1989, 1992; Burt *et al.*, 1998, Warburton, 1998; Demir, 2000). In the Lake District, records from the Iron Crag torrent weir also show flashy hydrograph response (Figure 3.6). Here rainfall events produce rapid rises in stream discharge and even minor runoff episodes are closely reflected in the streamflow. Larger flow peaks in upland streams create flood conditions that transport boulders, undermine hillslopes, and more rarely generate out of channel flows causing damage and disruption. The Lake District has a history of such damaging flood events, of which more detail is given in Chapter 7.

A further aspect of Lake District drainage is the regulation of flows and abstraction of water for supply purposes. Tarn and Wilson (1994) state that over the last 160 years increasing volumes of water have been abstracted from the Lake District, and state that about 30 % of piped water for the north west region originates in the Lake District. Figure 3.7 shows water is taken from Crummock Water (NY 160 190), Ennerdale Water (NY 110 150), Windermere (NY 000 390), Ullswater

Table 3.4: Contrasting characteristics of selected Cumbrian upland streams and lowland rivers.

Stream/ River details	Altitude difference (m)	Length (m)	Gradient ($m\ m^{-1}$)
UPLAND			
Doddick Gill (NY 330 270)	500	1400	0.357
Helvellyn Gill (NY 325 165)	510	2125	0.240
Lingmell Gill (NY 195 074)	635	2875	0.221
Piers Gill (NY 215 085)	600	1875	0.320
Sour Milk Gill (NY 167 156)	395	1000	0.395
Stickle Gill (NY 290 070)	380	1500	0.253
Tongues Gill (NY 348 108)	330	2000	0.165
Whelpside Gill (NY 330 140)	680	2175	0.313
Woodfell Gill (NY 475 105)	390	650	0.600
LOWLAND			
River Caldew (Caldbeck to River Eden confluence)	130	26,000	0.005
River Crake (Coniston Water to coast)	45	6000	0.008
River Derwent (Bassenthwaite Lake to coast)	71	29,500	0.002
River Eamont (Ullswater to Hornby Hall)	50	15,500	0.003
River Ehen (Ennerdale water to coast)	125	24,000	0.005
River Esk (Bottom of Hardknott Pass to coast)	95	23,000	0.004
River Kent (Kendal to coast)	35	12,250	0.003
River Leven (Windermere to coast)	40	10,000	0.004

(NY 390 180), and also from the Thirlmere (NY 310 710) and Haweswater (NY 480 140) reservoirs. NWW (2000) provides statistics to complement Figure 3.7, but these omit the quantity of water abstracted from Lake District sources. However, Haweswater and Thirlmere provide the most significant supplies. Haweswater has a capacity of 550 Ml d^{-1} and Thirlmere 250 Ml d^{-1}, contributing 40% of the water used by Bolton, Burnley, Kendal, Lancaster, Manchester, Oldham, Preston and Rochdale. Overall the Lake District supplies Manchester with 80 % of its water needs.

3.1.6 Soils and vegetation

Bendelow (1984) states that the soils of the Lake District are not typical of other parts of England. This is clearly evident on the 1: 250,000 soil map of northern England (Soil Survey of England and Wales, 1983) (Figure 3.8). The Lake District is dominated by soil units 311 (Humic rankers), 611 (Typical brown podzolic soils), and 1011 (Raw oligo fibrous peat soils) (Bendelow, 1984; Figure 3.8). Other soils include units 713 (Cambic stagnogley soils), 541 (Typical brown earths), 721 (Cambic stanohumic gley soils), and more localised areas of iron pan stagnopodzols (651). Pearsall and Pennington (1973) discuss soil types and note that like those of any upland area they represent a development series. Ranker soils (311) occur where lichens and mountain top plants build up humus amongst and over bedrock/ skeletal minerogenic soils. On the shoulders of fells and on steeper slopes more developed soils exist, namely brown earths where the surface layers are leached and have a mull humus, and soils with a mor humus and a podzolic transition in the underlying mineral soil, often found under *Calluna* vegetation (soil unit 611). Gleyed soils develop in waterlogged areas, often under *Juncus* vegetation, where the mineral soil has a characteristic blue-grey colour due to ferrous iron salts. Finally peat formations (soil unit 1011) occur where free drainage is impeded and mor humus transforms into peat (shallow peat). Blanket peat occurs on wide areas of flat/ gently sloping ground above 1500 ft (457 m), and contains wood fragments of the forests which once grew on these high plateaus.

Ratcliffe and Halliday (1997) provide a description of the contemporary vegetation of the Lake District, dividing it into three areas- lakes and valley bottoms, woods and lower ravines, and the fells. On the fells, early deforestation was followed by the

Figure 3.6: Iron Crag torrent weir flow stage

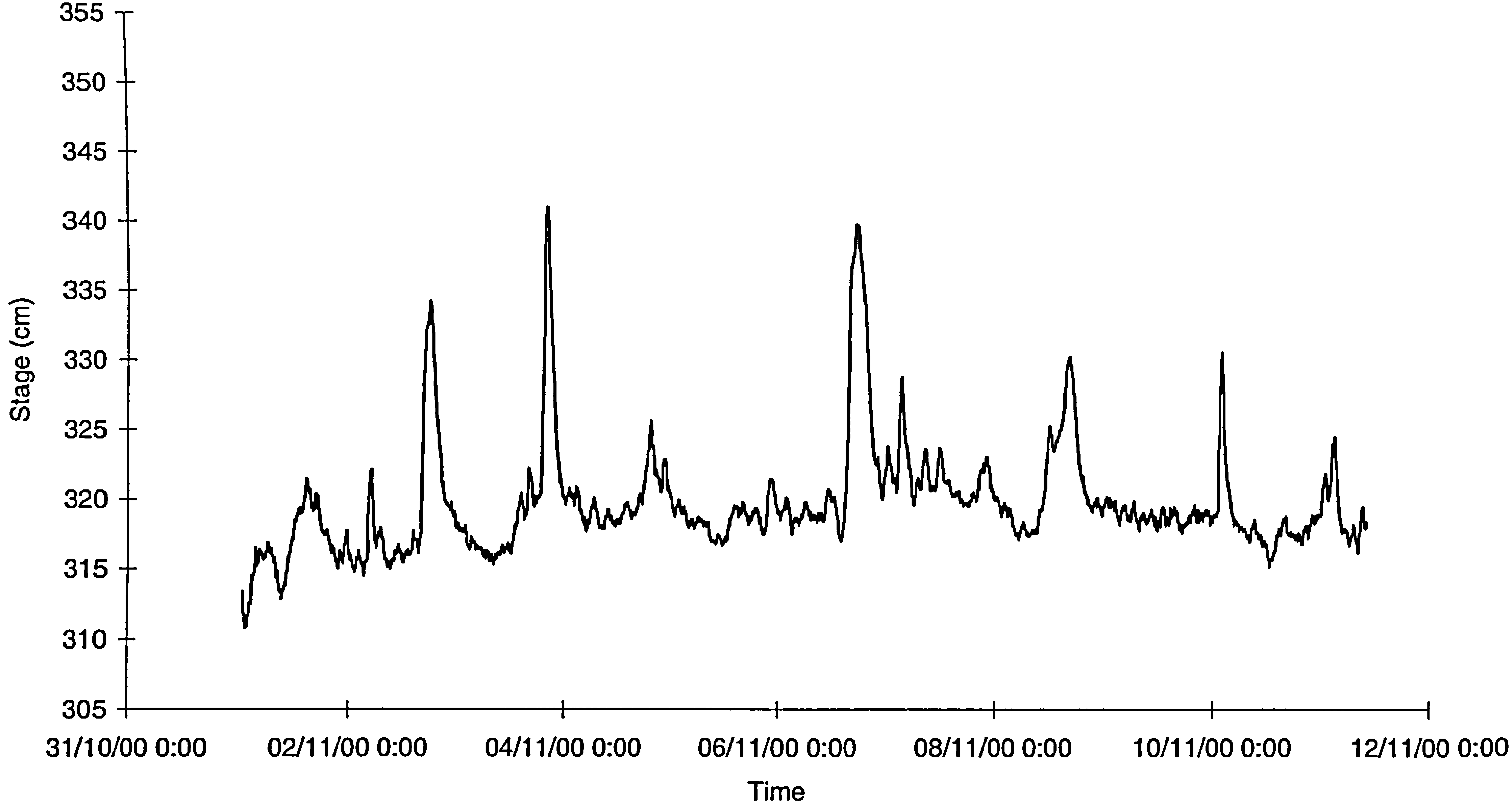
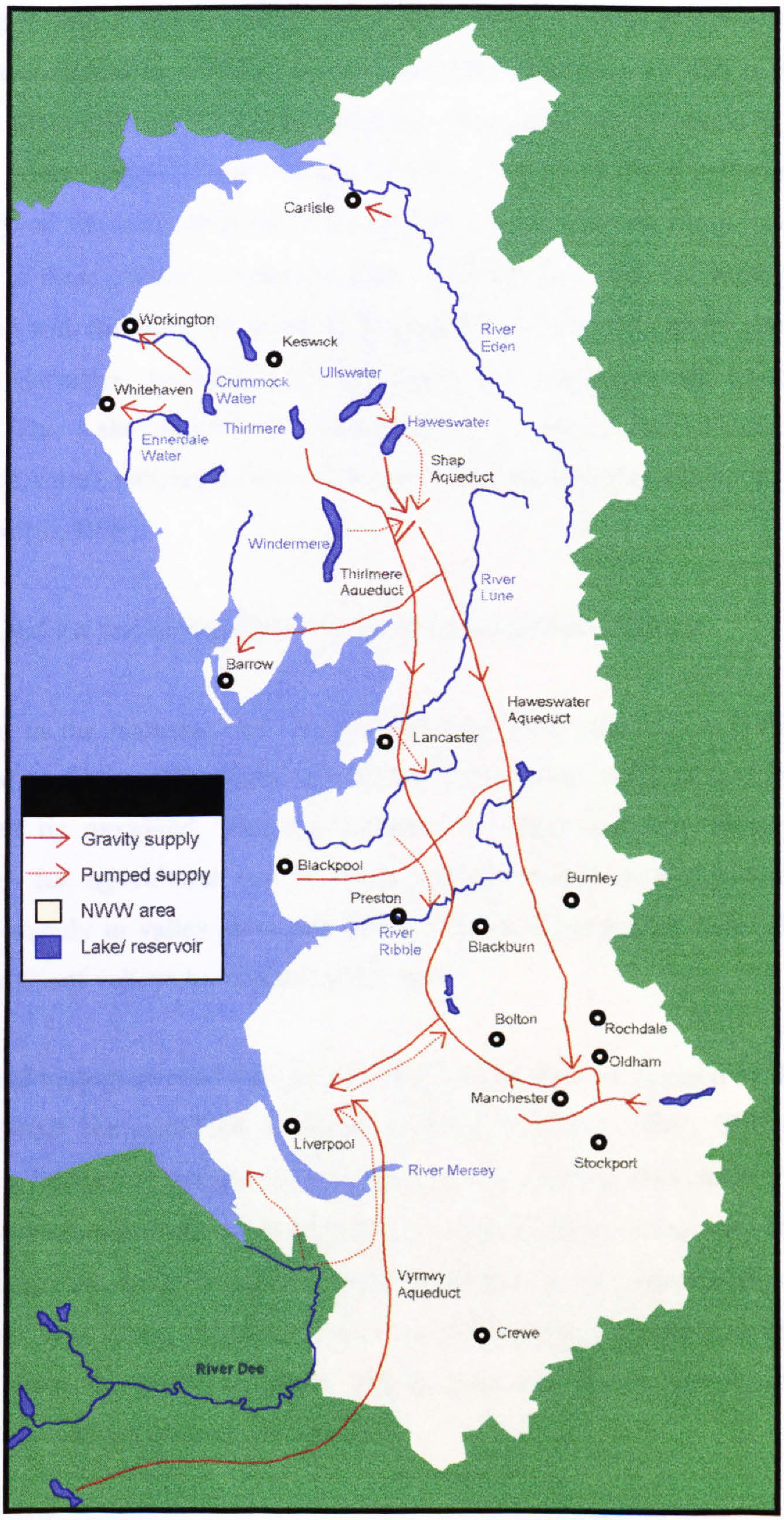


Figure 3.7: Major sources and aqueducts for the supply of water in the North West Water region. (Adapted From http: www.nwwnews.co.uk/ frames.asp, 18.12.00)



expansion of dwarf shrub heath (*Calluna vulgaris, Erica cinerea, Vaccinium myrtiluus*). More recently sheep grazing and moor burning have reduced the heath replacing it with acidic grasslands types (for example- *Festuca/ Agrostis; Nardus and Juncus* (Ratcliffe, 1997c)) and bracken (*Pteridium*) up to 450 m O.D. The Skiddaw Slate hills are the major remaining area of heather moorland in the Lake District, which Ratcliffe and Halliday (1997) consider to be a reflection of the chemistry of the soils that have discouraged high levels of sheep stocking. In addition to these general vegetation types, local habitats exist, for example, plants associated with the wet habitats in the Skiddaw area; calcicole alpines above 600 m O.D. on Helvellyn, Fairfield and High Street; and patches of oak woodland and Juniper. The Lake District is dominated by a sub-montane habitat (heaths, grasslands, mire), with small areas of montane habitats at higher elevations (Fielding and Haworth, 1999).

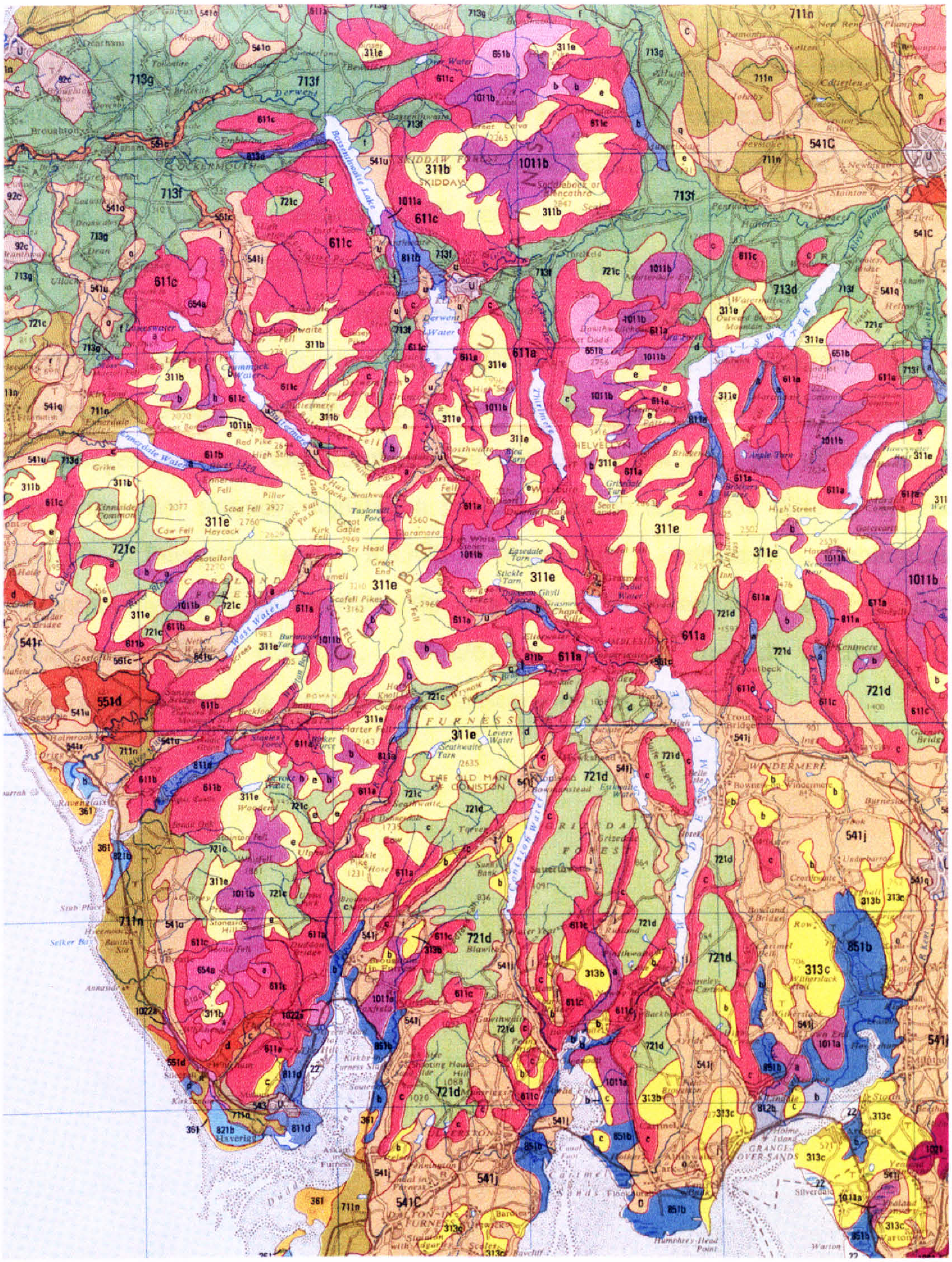
3.1.7 Land use and management of the Lake District National Park

Land use in the National Park is considered by Tarn and Wilson (1994) and is illustrated by Figure 3.9. Tarn and Wilson (1994) state much of the land area is dominated by moorland, with the inclusion of water and bare rock. The area remaining for agricultural use is small, indeed productive agricultural land is confined mainly to valley sides and floors. This is being further reduced with the emerging use of valleys for coniferous forestry.

The overall management of the Lake District National Park is outlined by the current 'Lake District National Park Management Plan' (LDNPA, 1999). This document provides a framework to conserve and enhance this National Park, secure the future of local communities, and allow the continued appreciation of the area. In this role the National Park Authority pursues these objectives in association with other local authorities, businesses, voluntary bodies and individuals. Complete details can be obtained from the report (LDNPA, 1999), here only further details of policies relating to rivers and erosion are outlined.

Erosion is considered as a result of sheep overgrazing, horse riding, mountain biking, fell walking, and vehicles. The greatest attention is given to overgrazing, and section

Figure 3.8: **Soil units in the Lake District National Park (Extract from soils of Northern England, 1: 250, 000, Soil Survey of England and Wales, 1983) (Copyright Cranfield University, SSLRC, 2001).**

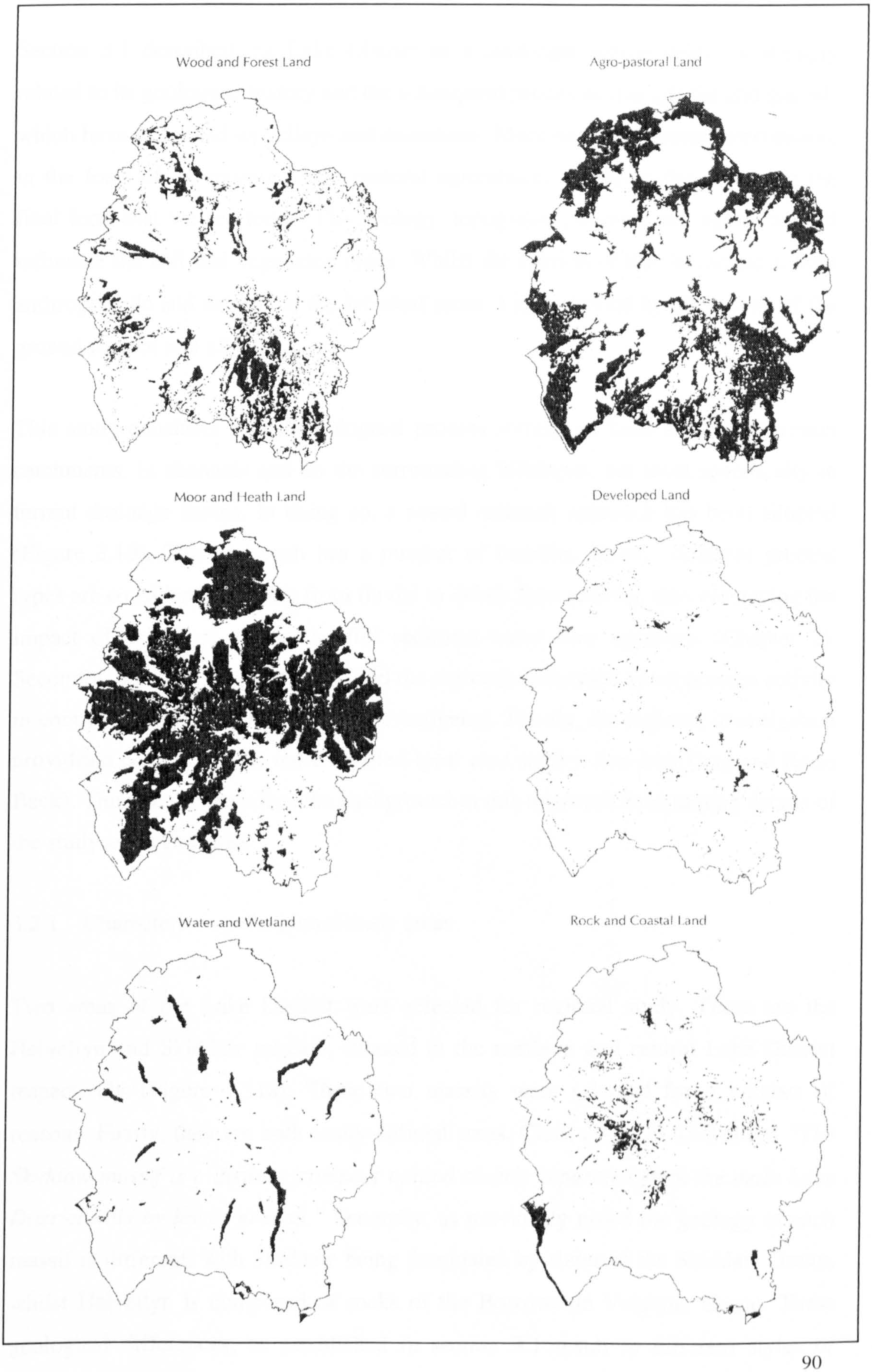


Dominant soil units:

311- Humic ranker
611- Typical brown podzolic soils
1011- Raw oligo-fibrous peat soils
713- Cambic stagnogley soils
721- Cambic stagmohumic gley soils
541- Typical Brown earths

6.13 of the Management Plan states the future vegetation and landscape of the fells is related to sheep farming, which in turn is determined by the agricultural support system. Grazing maintains the diversity of grassland and moorland, but where stocking is too high physical erosion can occur. To reduce stocking numbers the 'Environmentally Sensitive Area' (ESA) scheme ensures income for farmers that reduce sheep numbers. However, in areas of land under common ownership this scheme has had little success, e.g. in the Caldbeck Fells stocking numbers remain too high for ESA support (Eastman, 2000 personal communication). With regard to rivers the overriding emphasis of the management plan is upon the ecology of the aquatic environment and their recreational value. The Lake District National Park Authority acknowledges (section 3.33- LDNPA, 1999) that the National Park is important for geology and geomorphology, but gives this little overall emphasis in the management plan. Geomorphological and geological sites are offered some protection under statutory legislation for conservation e.g. SSSI (Site of Special Scientific Interest) and RIGGS (Regionally Important Geological/ Geomorphological Sites). Similarly, the area-specific Skiddaw massif and Helvellyn Management plans (LDNPA, 1997a/b) make only limited reference to geomorphology, again in the context of conservation legislation.

Figure 3.9: Land use in the Lake District National Park (from Tarn and Wilson, 1994)



3.2 Description of study sites and the nested research approach

Section 3.1 described the Lake District as a landscape whose origin is strongly related to its geological history and the subsequent processes (periglacial and glacial) which have fashioned its valleys and mountains. More recently, human intervention, in the form of deforestation and pastoral agriculture, has given the landscape the final form that we see today. The geology, topography, climate and agriculture all influence the soil and vegetation types. Whilst the erosion of this landscape is both anthropogenic and natural, in the broadest sense it is controlled by interaction of the ground surface and climate.

This study considers geomorphological process activity in Lake District mountain catchments, in channels and on the surrounding hillslopes, but most specifically in torrent drainage basins. In doing so, a nested research approach has been adopted (Figure 3.10). This approach has a number of benefits. Firstly, different process types are considered, ranging from fluvial to debris flow activity, thus embracing the impact of processes across the full sediment-water flow spectrum (Chapter 2). Secondly, both the case study sites and the regional evaluation allow process activity in contrasting geological areas to be investigated. Thirdly, the regional investigation provides a context for the more detailed local case studies (i.e. Iron Crag and Raise Beck). This section describes the background to this approach by outlining details of the study areas and sites.

3.2.1 Characteristics of regional study areas

Two areas of the Lake District were selected for regional study. These are the Helvellyn and Skiddaw massifs, situated in the northern and central Lake District respectively (Figure 3.11a). These two massifs were selected for a number of reasons. Firstly, they are both easily defined areas. Clark (1994, p 437) states *"The Skiddaw massif is a distinct, compact upland clearly separated from the main Lake District hills by lower ground."* Secondly, as previously noted the geology of each massif is different, with Skiddaw being dominated by slates of the Skiddaw Group, whilst Helvellyn is composed of rocks of the Borrowdale Volcanic Group. These geological differences, as established in section 3.1 result in different styles of

Figure 3.10: Conceptual model of the nested research approach applied to the study of Lake District mountain catchments. This shows the relationship between the three main study elements: regional surveys; sediment budget monitoring (Iron Crag) and flood reconstruction (Raise Beck)

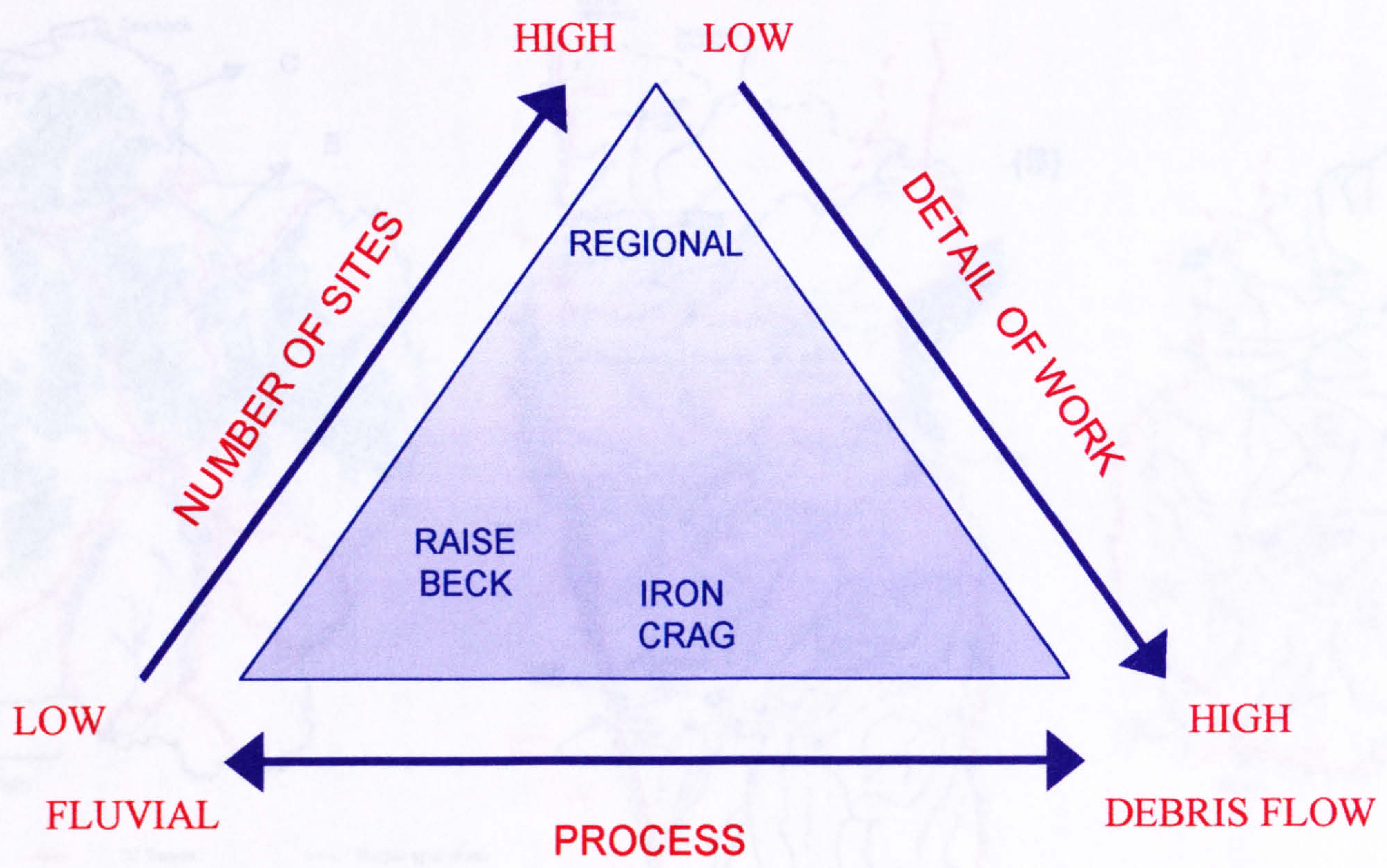
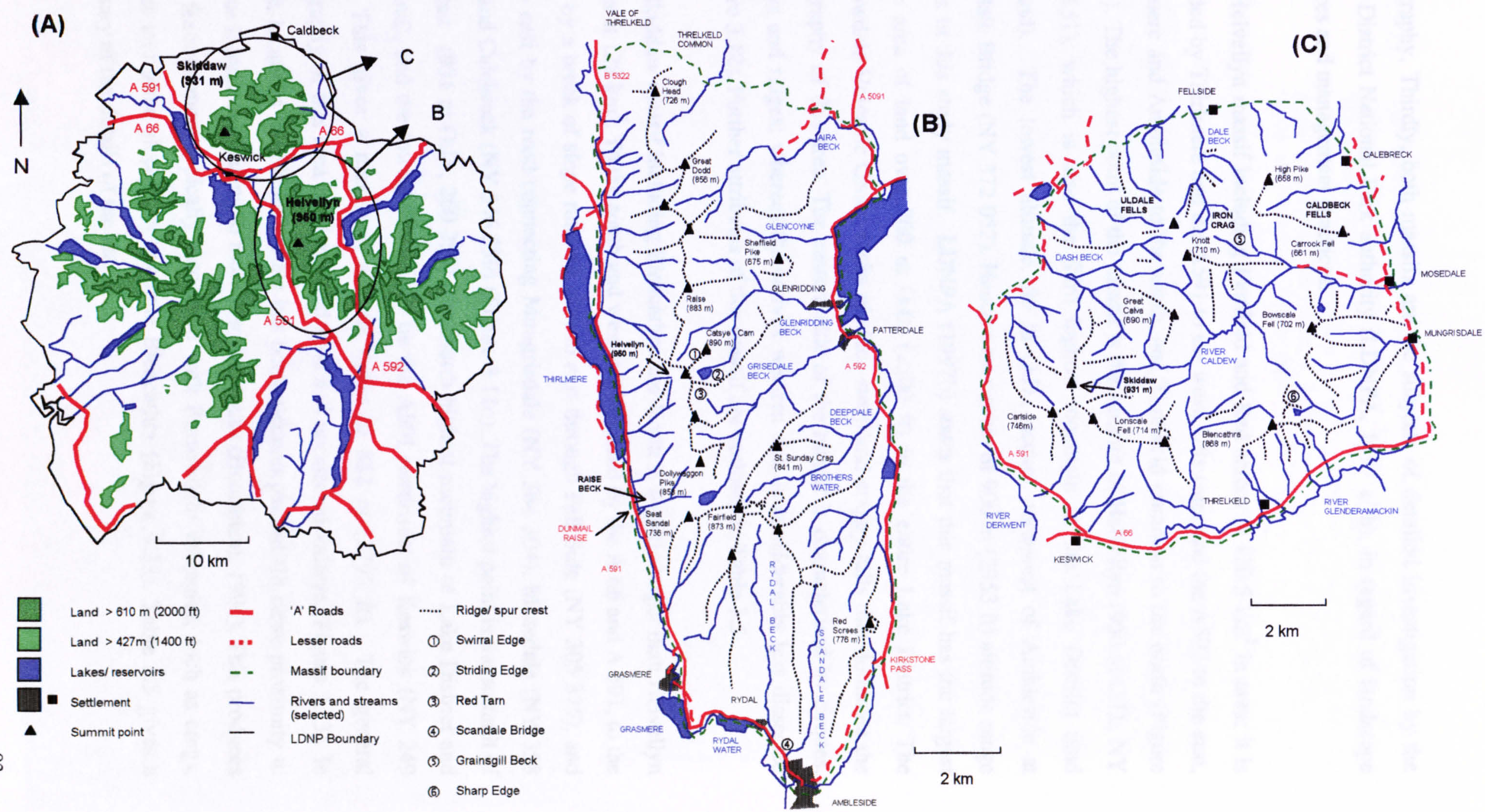


Figure 3.11: The Helvellyn and Skiddaw massif regional study areas (A- Lake District, B- Helvellyn massif, C- Skiddaw Massif)



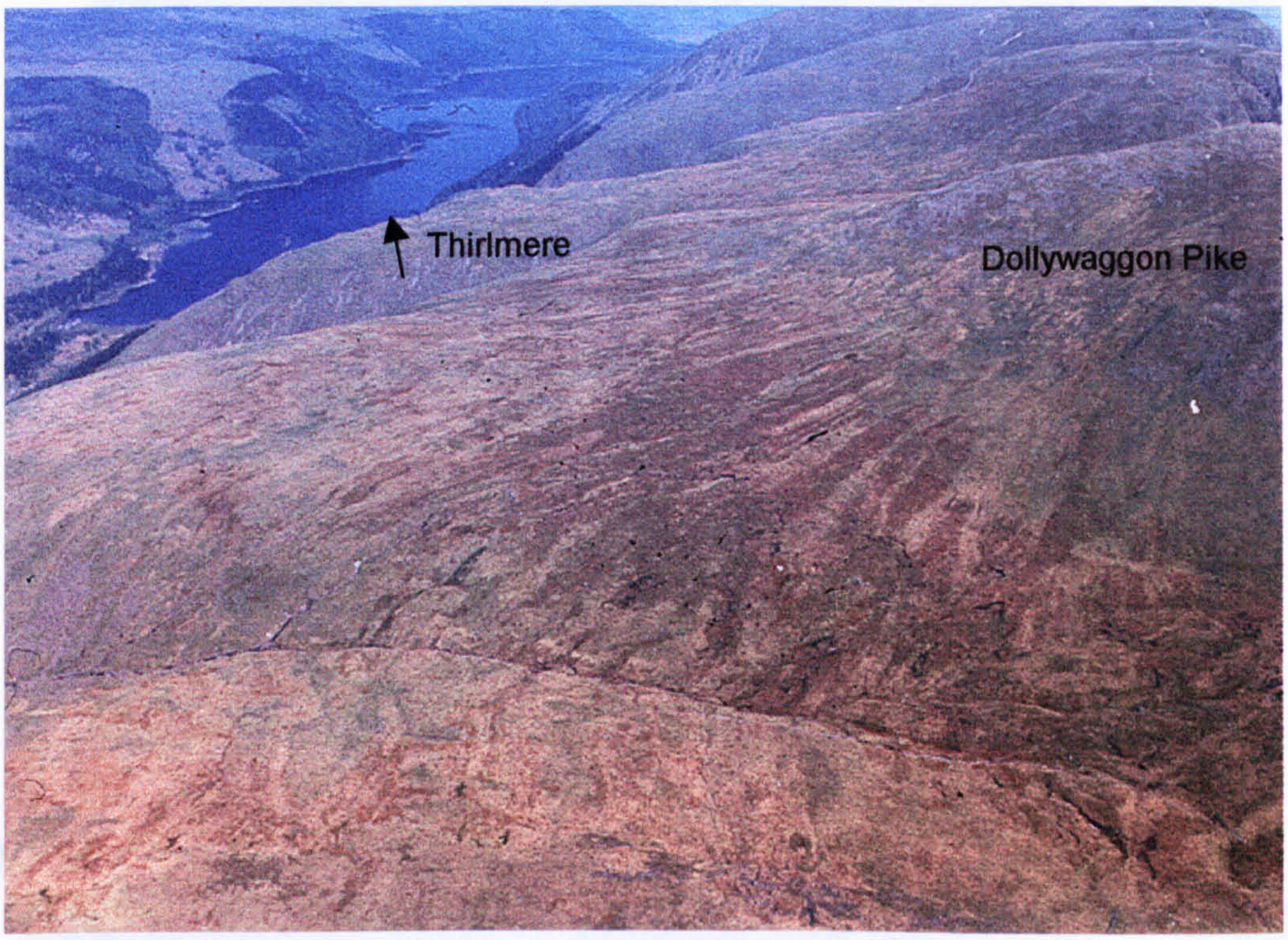
topography. Thirdly, both massifs are the subjects of detailed investigation by the Lake District National Park authority (LDNPA, 1997 a/ b), in regard of landscape features and management practices.

The Helvellyn massif including Fairfield and Red screes is 120.5 km^2 in area; it is bounded by Thirlmere and the A591 to the west, Ullswater and the A592 to the east, Grasmere and Ambleside to the south, and Threlkeld common to the north (Figure 3.11b). The highest point of the massif is the summit of Helvellyn (950 m O.D., NY 341 151), which is also the third highest mountain in the Lake District (and England). The lowest altitude, 50 m O.D., occurs northwest of Ambleside at Scandale Bridge (NY 372 052). Hence a maximum of 900 m (2953 ft) altitude range occurs in this study massif. LDNPA (1997b) states that this massif has the largest single area of land over 760 m O.D. (2500 ft) in the entire Lake District. The Borrowdale Volcanic Group rocks produce steep and craggy hills that dominate the topography of this area. The eastern side of the massif is characterised by cirques, valleys and ridges; whereas the convex western side is considerably less dissected (Figure 3.12). Further attributes of this massif are outlined in Table 3.5

The Skiddaw massif including Blencathra and Knott is slightly larger than Helvellyn in area at 128 km^2. To the south and west it is bounded by the A 66 and A 591, to the north by a break of slope running west to east through Fell Side (NY 305 375), and to the east by the road connecting Mungrisdale (NY 364 304), Mosedale (NY 358 323) and Calebreck (NY 346 359) (Figure 3.11c). The highest point is the summit of Skiddaw (931 m O.D., 260 290) (the fourth highest mountain of Lake District and England), and the lowest 79 m O.D. on the A591 northwest of Keswick (NY 249 262). This gives a maximum altitude range of 852 m (2795 ft). The general topography of this area is of rounded hills and occasional valleys (Figure 3.13). In certain locations the Skiddaw slate has been metamorphosed (in close proximity to igneous intrusions) leading to more resistant rocks (Boardman, 1996). This produces local features more typically associated with Borrowdale volcanics, such as crags, cirques and scree slopes, for example Blencathra (Figure 3.13). Table 3.5 gives a summary of the details of the massif.

Figure 3.12: Characteristic landscape features of the Helvellyn massif. (A) Convex west slopes of the summit ridge, looking north from above Seat Sandal (NY 344 115), with Dollywaggon Pike (NY 346 131) in the foreground and Thirlmere Reservoir in the background. (B) Deep dissection on the eastern side of summit ridge caused by glacial erosion and stream activity, looking west to Striding Edge, Helvellyn summit (NY 341 151), Swirral Edge, and Red Tarn.

(A)



(B)

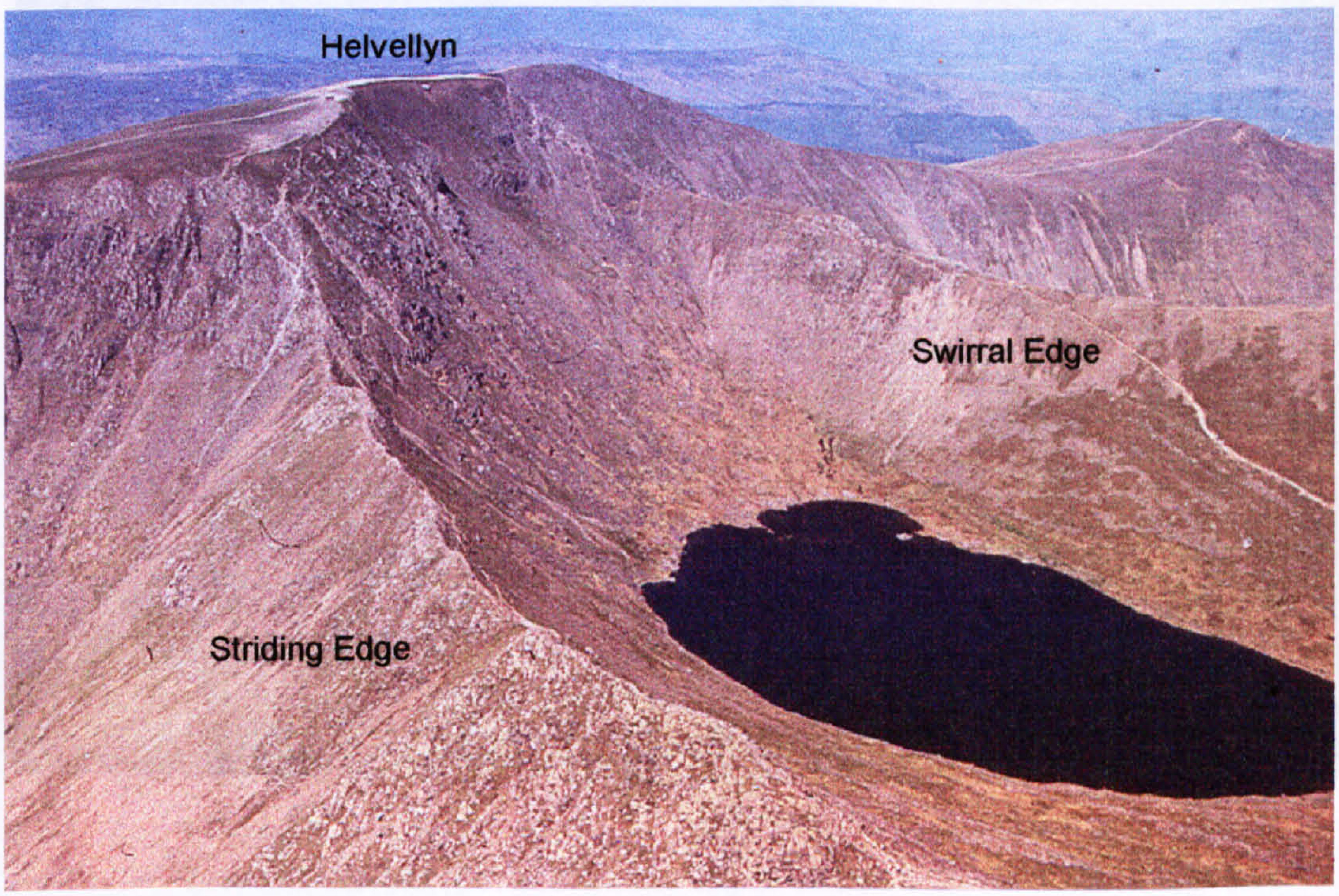
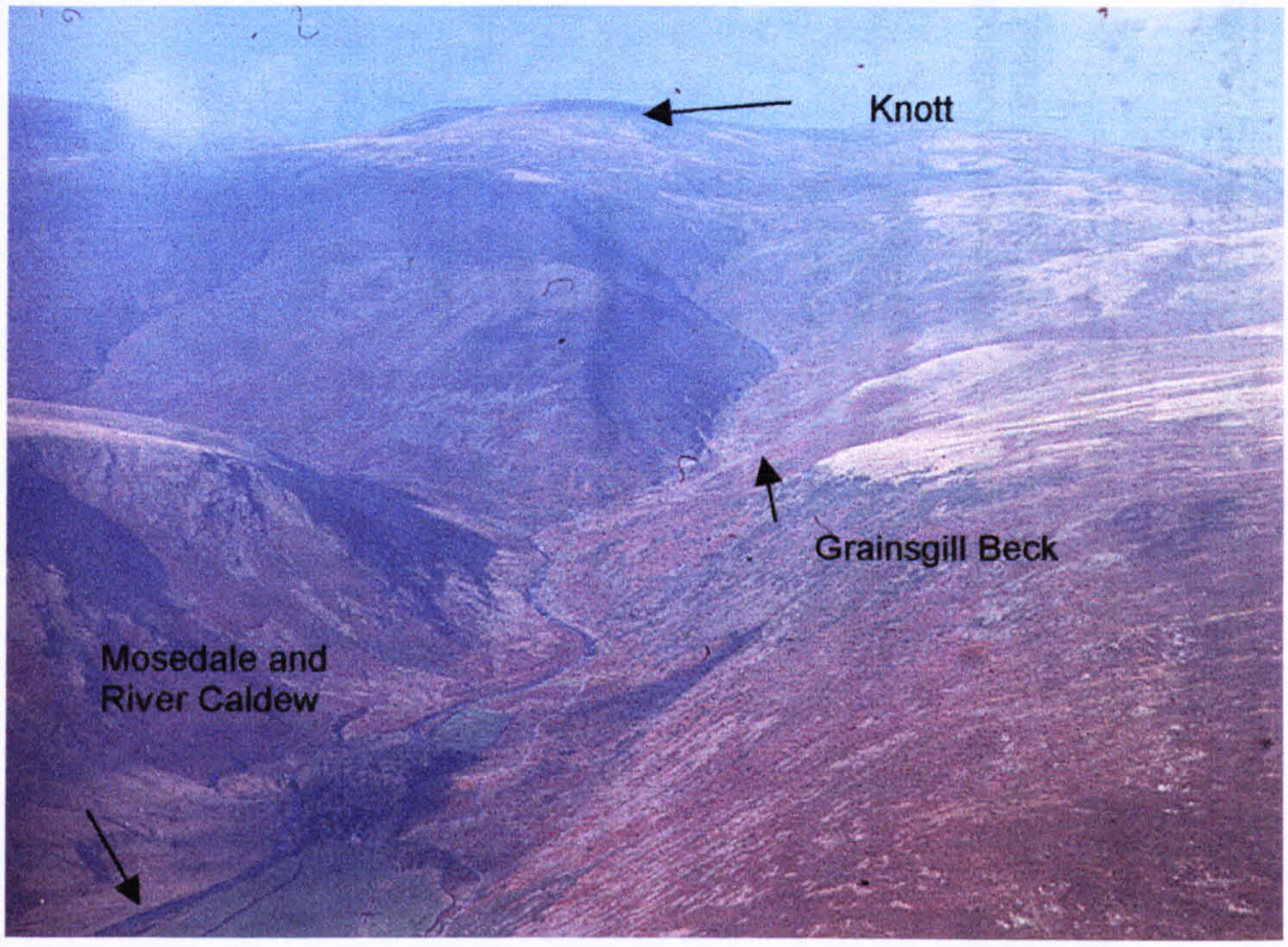


Figure 3.13: Characteristic landscape features of the Skiddaw massif. (A) Rounded topography; view up Mosedale and Grainsgill Beck towards Knott (NY 295 330). (B) Localised crag and cirque forms; Sharp Edge and Scales Tarn on the north east side of Blencathra (NY 326 282)

(A)



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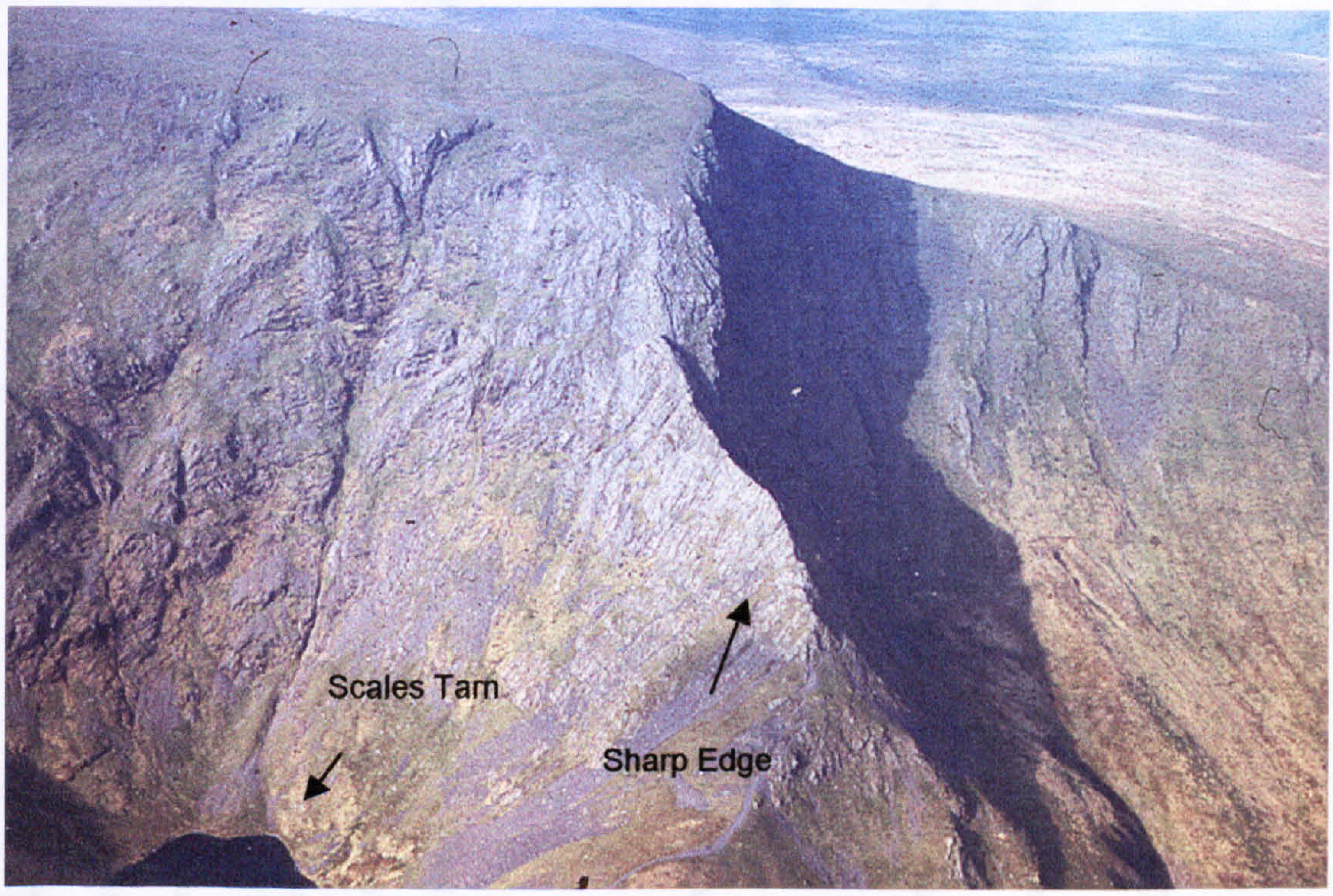


Table 3.5: A comparison of the characteristics of the Helvellyn and Skiddaw mountain massifs.
(RIGS- Regionally Important Geological and Geomorphological Sites; GCR- Geological Conservation Review sites
SAMS- Scheduled Ancient Monuments, SSSI- Site of Special Scientific Interest, ESA- Environmentally Sensitive Area)

Characteristic	Helvellyn	Skiddaw
Maximum altitude (m O.D.)	950	931
Minimum altitude (m O.D.)	50	79
Maximum altitude difference (m O.D.)	900	852
Massif area (km^2)	120.5	128.5
Main geology type (s)	1. Borrowdale Volcanics Group 2. Skiddaw Group	1. Skiddaw Group slates 2. Skiddaw Granite 3. Carrock Fell Complex 4. Eycott Group volcanics 5. Carboniferous limestone
Soil units	611 (Typical brown podzolic soil) 311 (Humic rankers) 1011 (Raw oligo-fibrous peat soil)	Dominated by 311, 611,1011. Lesser quantities: 713 (Cambic stagnogley soil) 541 (Typical brown earth) 651 (Ironpan stagnopodzols)
Vegetation	Woodland, heather heath, grass, bracken, conifer plantations, juniper, calcicole arctic/ alpine plants	Heather, Bracken, local mixed woodlands, conifer plantations, blanket peat, gorse, juniper, grass
Land ownership	LDNPA, National Trust, North West Water Ltd, and private	LDNPA, and private
Management designations/ schemes	SSSI, ESA (others unknown)	SSSI, ESA, RIGS (10) , GCR (12), SAMS (1)

Within the two massifs mountain torrents, mountain streams, and hillslope debris flows have been investigated as part of the regional phase of this study. Results are given in Chapter 8. Iron Crag and Raise Beck are two sites within these massifs, where detailed site investigations were undertaken. Iron Crag the focus of a sediment budget study given high process rates. A detailed flood history is established for Raise Beck given abundant palaeoflood evidence. Before describing the detail of each site (section 3.2.2- 3.2.3) Table 3.6 gives the characteristics of both Iron Crag and Raise Beck. Raise Beck is both higher in maximum altitude and altitudinal difference, and also has a considerably larger drainage catchment. The sites have contrasting geology, Iron Crag being part of a local igneous intrusion, and Raise Beck on the more widespread Borrowdale Volcanic Group. Soil types, land ownership and management practices also vary between the two (Table 3.6).

3.2.2 Iron Crag torrent, Caldbeck Fells (Skiddaw massif)

Iron Crag (NY 305 341) is a small (2.4 ha), active torrent in the Caldbeck Fells, Northern Lake District (Figure 3.14). Situated 3.4 km south of Fellside, and 0.5 km north-west of Great Lingy Hill (NY 310 339, 610 m O.D.) at the head of the Dale Beck valley. Its morphology consists of multiple hillslope sediment sources, a main channel and a basal fan deposit (Figure 3.15). These morphological-process zones were further subdivided. Figure 3.16 identifies hillslope sediment sources in four areas, known as the primary zone, sub-primary zone, secondary zone, and the bedrock outcrop zone. The channel system and fan are treated as separate zones. More detailed discussion of these segregation's are given in section 5.1. The highest altitude of the catchment is 600 m O.D., and the fan toe is at 395 m O.D. (Table 3.6). Maximum slope angles are around 45 degrees, with an overall catchment slope of 0.273 m m^{-1} (Table 3.6).

Chapters 4 and 5 show process activity at Iron Crag across the full sediment-water flow spectrum, involving both fluvial and debris flow activity. Fluvial processes are shown to be far more frequent (though the less frequent channelised debris flows can have a large impact on the system causing significant amounts of sediment movement). Sediment is actively supplied from several components of the system, i.e. hillslopes, channel bed, and banks. Base flow is fed by springs at the top of the

Table 3.6: A comparison of the characteristics of the Iron Crag and Raise Beck torrents (GCR- Geological Conservation Review sites, SSSI- Site of Special Scientific Interest, ESA- Environmentally Sensitive area)

Characteristic	Iron Crag catchment	Raise Beck catchment
Maximum altitude (m O.D.)	600	858
Minimum altitude (m O.D.)	395	235
Maximum altitude difference (m O.D.)	205	623
Catchment area (ha)	2.4	133
Mean catchment slope ($m\ m^{-1}$)	0.273	0.249
Aspect (magnetic bearing, degrees)	350 (N)	261 (W)
Geology type (s)	Iron Crag microgranite	Borrowdale Volcanic Group
Soil units	1011 (Raw oligo-fibrous peat soil) 651 (Ironpan stagnopodzols)	611 (Typical brown podzolic soil) 1011 (Raw oligo-fibrous peat soil) 311 (Humic rankers)
Vegetation	Grasses	Grasses, and Bracken
Land ownership	Caldbeck common (LDNPA)	North West Water Ltd, National Trust
Management designations/ schemes	SSSI, GCR	ESA

Figure 3.14: Iron Crag and the Caldbeck Fells: (A) Skiddaw Massif, (B) Iron Crag and the Dale Beck Valley

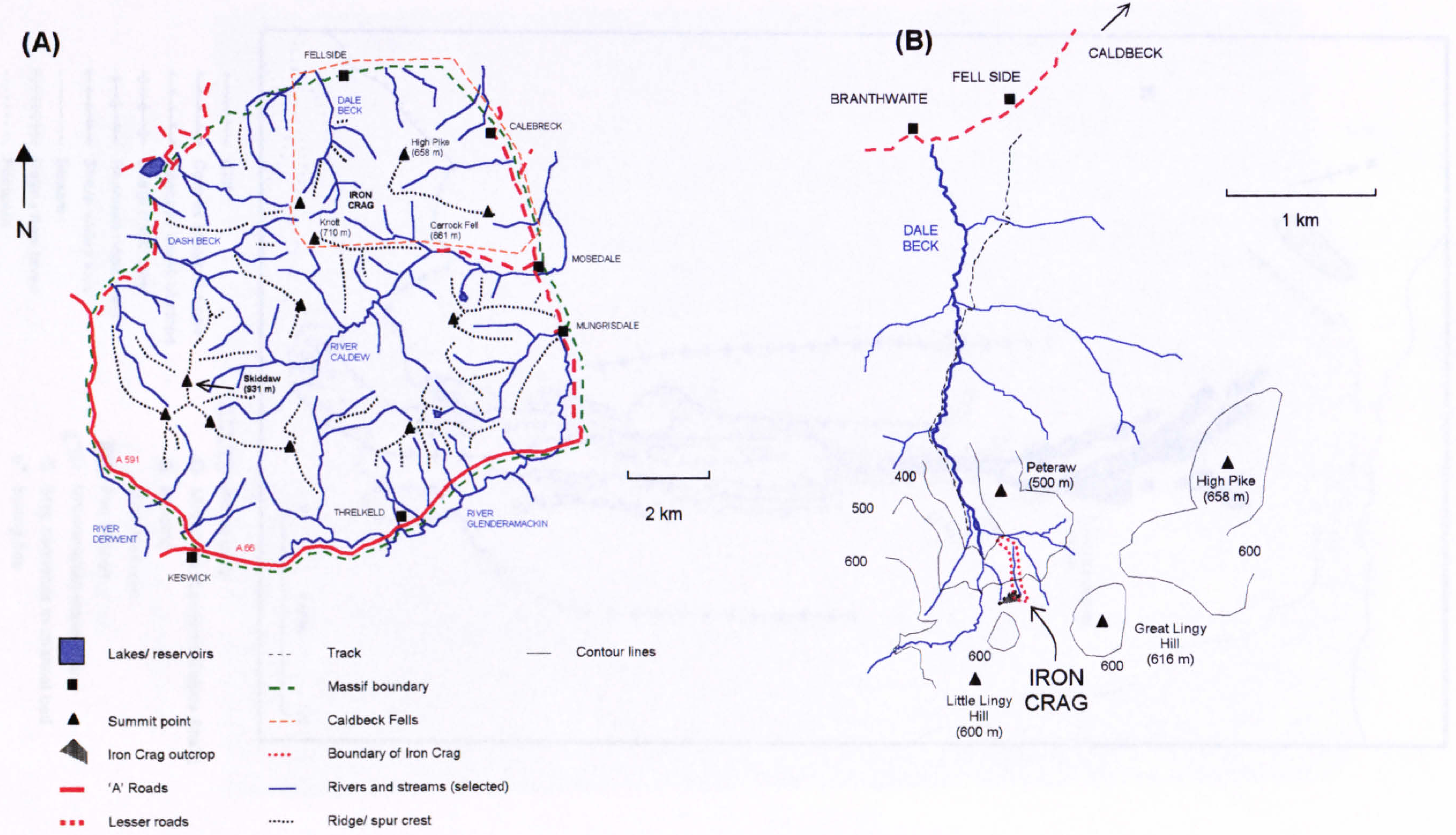
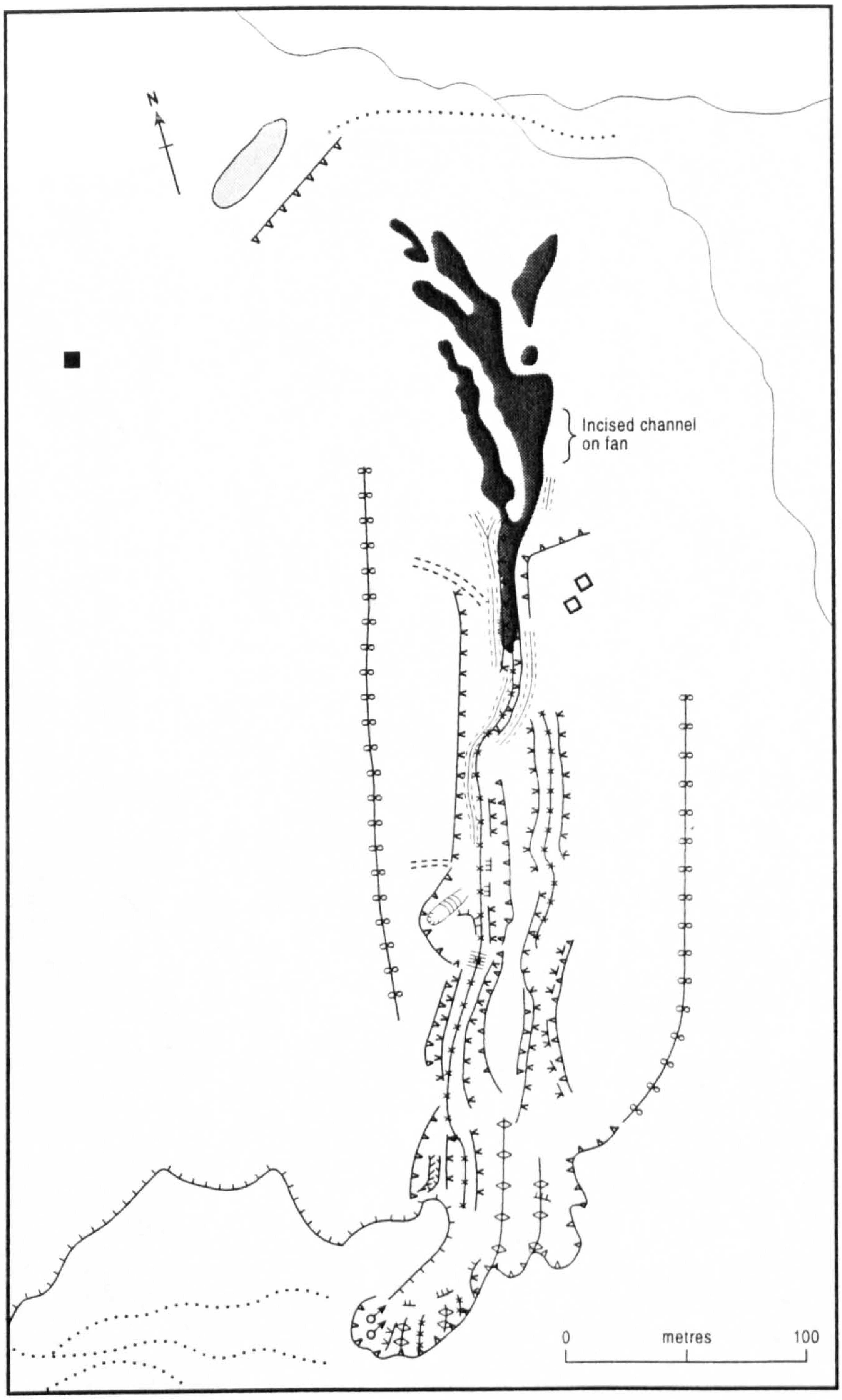
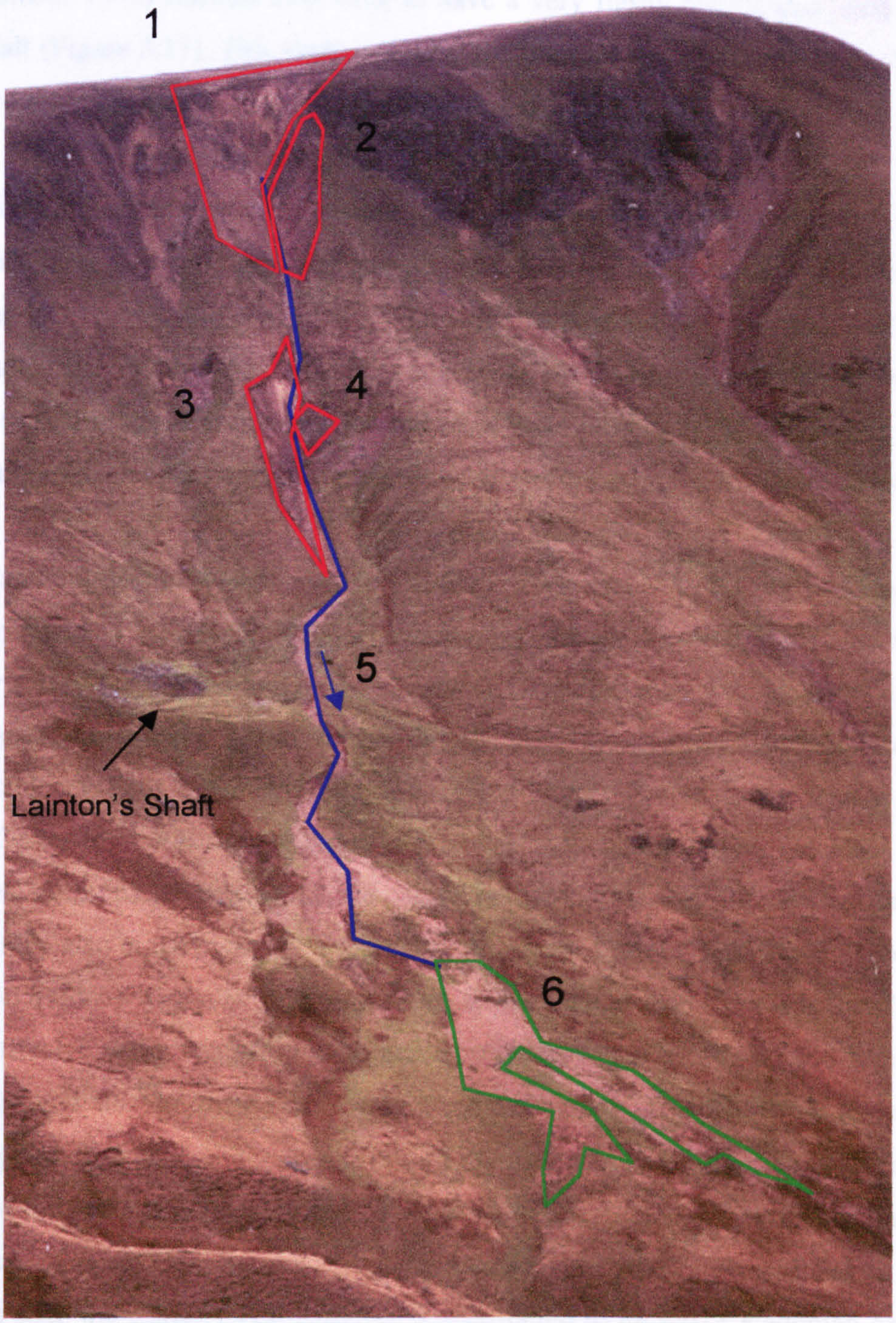


Figure 3.15: Geomorphological map of the Iron Crag torrent, derived from aerial photography and field reconnaissance



- Cliff
- Convex break of slope
- Concave break of slope
- Sharp ridge crest
- Rounded ridge crest
- Sharp valley axis
- Stream
- Debris flow levee
- Footpath
- Track
- Active gully
- Mine ruins (Lainton's Engine Shaft)
- Building
- Mine reservoir
- Fan deposit
- Unconnected slope failure
- Step sequence in channel bed
- Spring line

Figure 3.16: **Iron Crag morphological zones, superimposed on a photograph of Iron Crag taken from Peteraw (500m O.D. NY 304 348)**



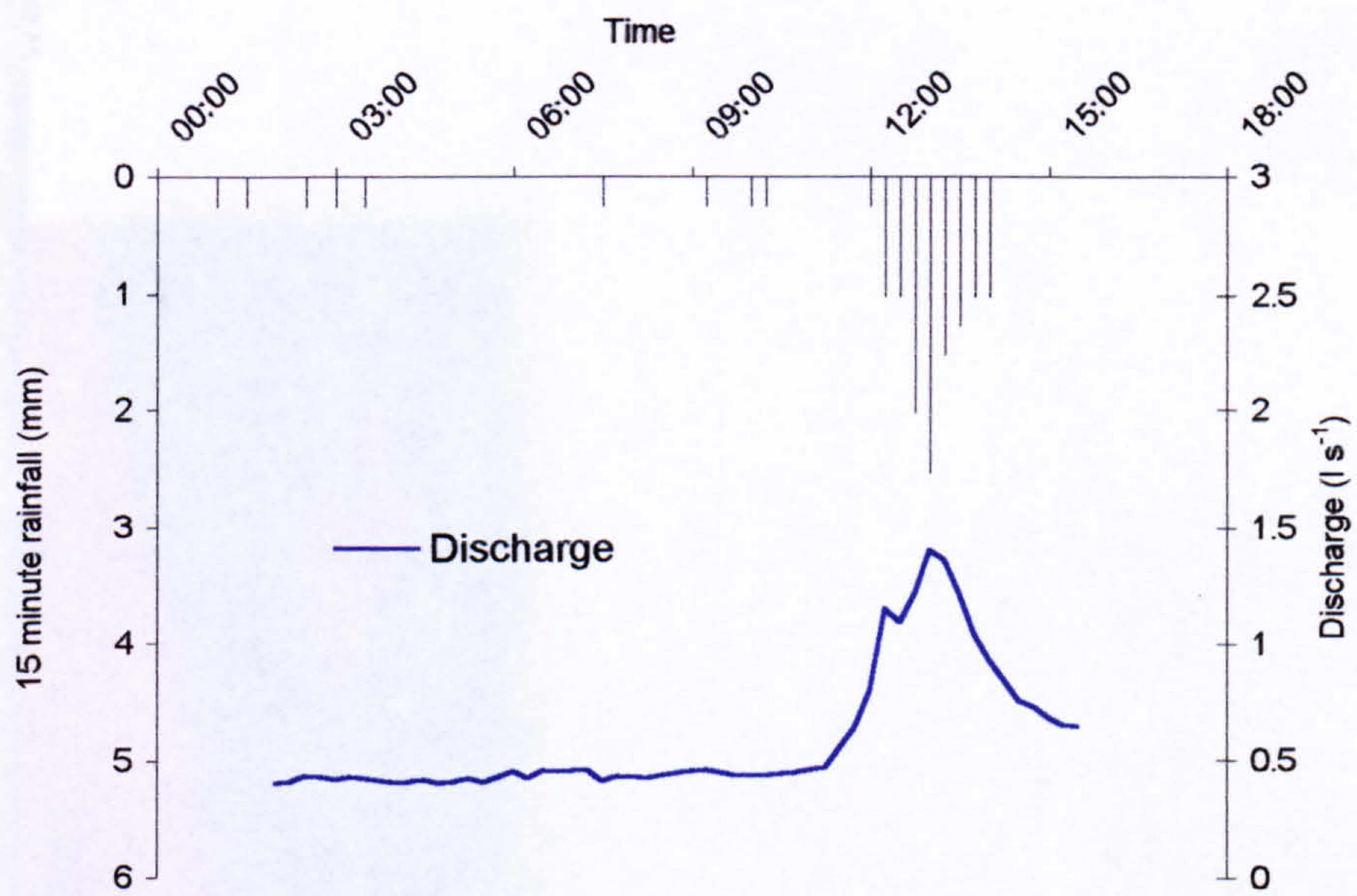
1:Primary hillslope zone
2:Sub- primary hillslope zone
3:Secondary hillslope zone
4:Bedrock step hillslope zone
5:Channel
6:Active fan deposit

gully system (see Figures 3.15-3.16). During storm periods water is also supplied from the head of the system as overland flow, throughflow and minor pipeflow. A pilot study of the discharge and suspended sediment response to a storm (26th November 1999) showed Iron Crag to have a very flashy hydrological response to rainfall (Figure 3.17). This study provided the impetus for the construction of a weir for continuous measurements (a selection of results are previously shown- Figure 3.6). Figure 3.17 shows that through the morning of the 26th November 1999 rainfall was intermittent achieving 15 minute intensities of only 0.254 mm. At 12.15 (GMT) rainfall increased to 1 mm and peaked at 2.54 mm in 15 minutes at 13.00. The discharge of water also peaked at 13.00 with a flow of 1.4 l s^{-1}, and then declined as rainfall intensities reduced, but did not achieve pre-storm baseflow levels after the cessation of rainfall. The suspended sediment yield peak (330 mg l^{-1}) slightly lagged the rainfall peak by 15 minutes, and thereafter rapidly declined to pre-storm levels.

In examining torrent activity in the Caldbeck Fells and at Iron Crag two important factors need to be considered: the underlying geology, and the associated mining history. Day (1974) states that the Caldbeck Fells is classic ground, for it exhibits geological and mineralogical variety. Indeed Cooper and Stanley (1990) indicate that the Caldbeck Fells have a complex geological history. On the outer fringes of the fells Carboniferous limestone is present. In the north lie the Eycott volcanics whilst further south rocks belong to the Skiddaw Group; all are of Ordovician age. Intrusions also exist, most significantly rocks of the Carrock Fell plutonic complex and the Skiddaw Granites (Figure 3.18 a). In the case of Iron Crag it is the Carrock Fell intrusive rocks which are most relevant. Eastwood *et al.* (1968) and Woodland (1977) show the head of Iron Crag to be composed of Granophyre (Iron Crag microgranite), and possibly some Gabbro, dissected by two south west- north east aligned mineral veins (Figure 3.18 b). The exact age of the Carrock Fell intrusion is a matter of debate. Earlier accounts, i.e. Eastwood *et al.* (1968) and Taylor *et al.* (1971) state the Carrock Fell complex is considered to be post Caledonian orogeny (late Silurian) and pre Carboniferous in age, probably in the Devonian. More recent publications cite an older age. Firman (1978) considers the age of the Granophyre intrusions to be uncertain, in chronological terms they fall between the Ordovician Eycott Volcanics and the Devonian Skiddaw Granite. Rundle (1979) dated the Carrock Fell Granophyre using Rubidium- Strontium

Figure 3.17: Hydrological monitoring of rainfall and discharge series, Iron Crag, 26.11.99. (A) Rainfall and discharge, (B) Suspended sediment concentration

(A)



(B)

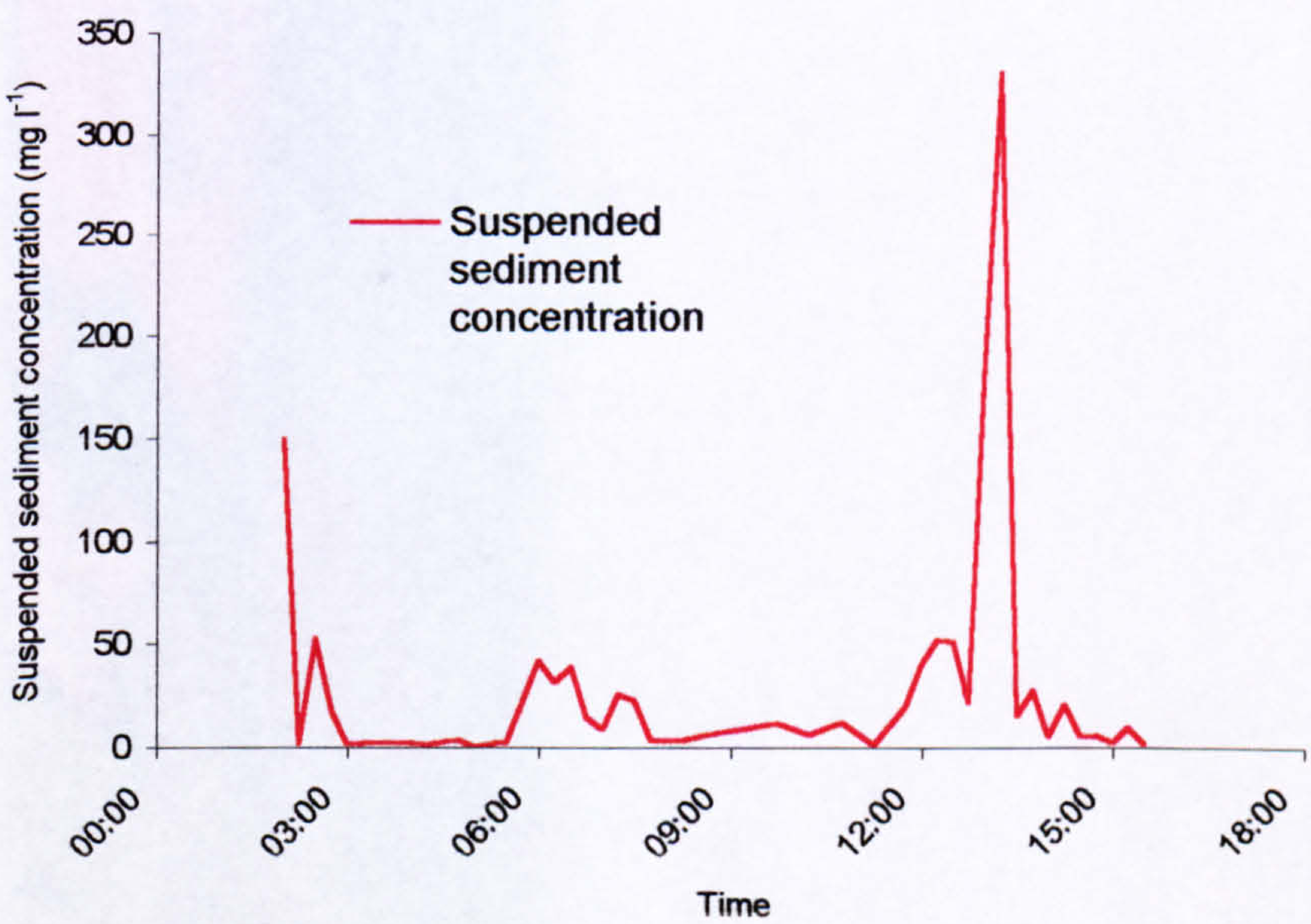
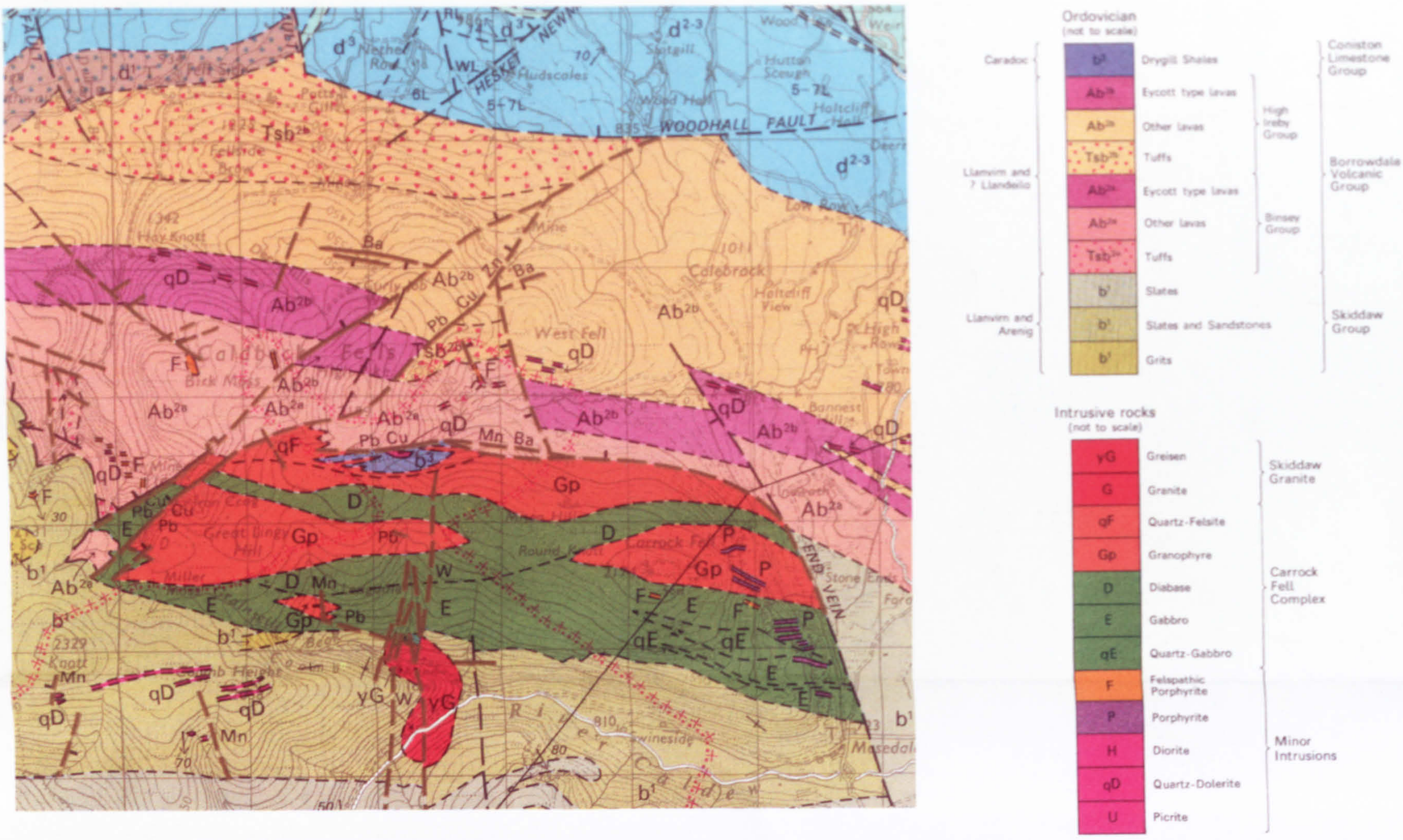
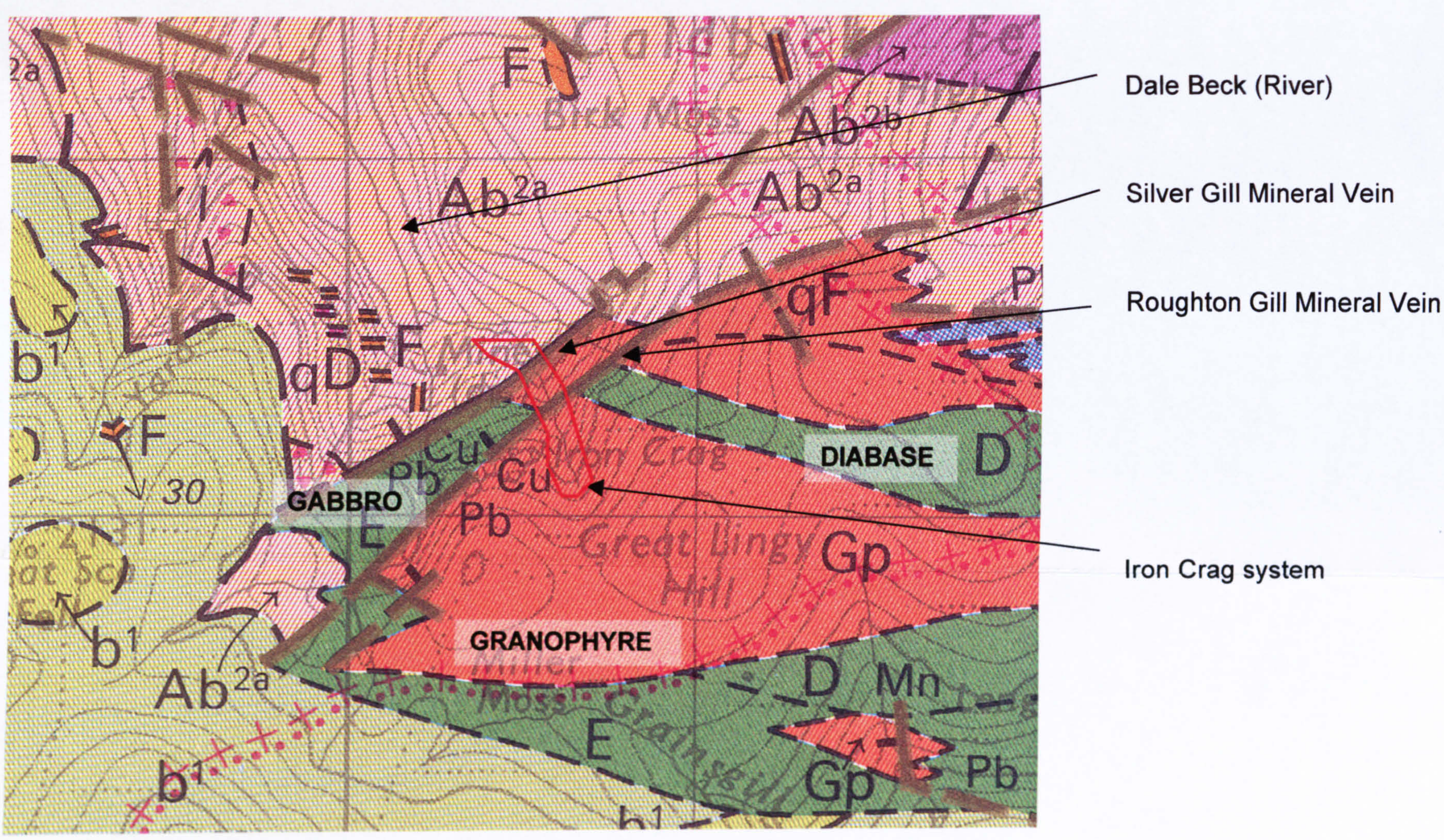


Figure 3.18: (A) Solid Geology of part of the Caldbeck Fells, (B) Solid geology of Iron Crag and the immediate area
Based upon Woodland, 1977: Cockermouth Sheet 23, 1:50 000 Series, by permission of the British Geological Survey.

(A)



(B)



(Rh- Sr) dating to 416 ± 20 Ma (Silurian), though Rundle (1979) and O'Brien *et al.*(1985) consider this date to be subject to error. Most recently Cooper and Stanley (1990) place the entire intrusion in the late Ordovician.

At the base of the Iron Crag system, below the Silver Gill vein, the solid geology is that of Eycott volcanics (Woodland, 1977). However Dunham (1975) does not show the solid geology, as drift deposits (mainly glacial boulder clay) mantle the landscape. Locally the drift geology is far more complex.

The Caldbeck Fells has a rich history of mining, and is considered a very important mineralogical area on both a national and international scale. This is reflected in reports of the area, for example:

"Caldbeck and the Caldbeck Fells are worth all England else" (Hutchinson, 1794)

"The Caldbeck Fells District is a rich mining field.." (Postlethwaite, 1913)

"The mines and mineral veins of the Caldbeck Fells have produced some of the finest mineral specimens ever found..." (Cooper and Stanley, 1990)

Here the account of mining is restricted to activity immediately in the vicinity of Iron Crag, for detailed accounts of mining in the Caldbeck Fells consult Postlethwaite (1913), Day (1928), Shaw (1970), Adams (1988), Cooper and Stanley (1990), Donald (1994). Roughton Gill mines is a general term given to the Roughton Gill, Silver Gill and Mexico Mines at the head of the Dale Beck Valley (Adams, 1988). Roughton Gill was the most productive mine of the entire Caldbeck Fells in both quantity and variety of ores and minerals (Postlethwaite, 1913). The primary ores extracted from these mines were lead, copper and zinc (Adams, 1988). Shaw (1970) considers mining at this valley head to have begun in the 12th Century, but was generally idle until mined by the Elizabethans in 1566. Extensive activity began in the latter part of the 18th Century, until closure in 1878. Cooper and Stanley (1990) point out following the closure of the mine, some reworking of the mine dumps was carried out until 1894. A 'great flood' in 1895 is considered to have carried away half of the mine dumps, scattering the material down Dale Beck.

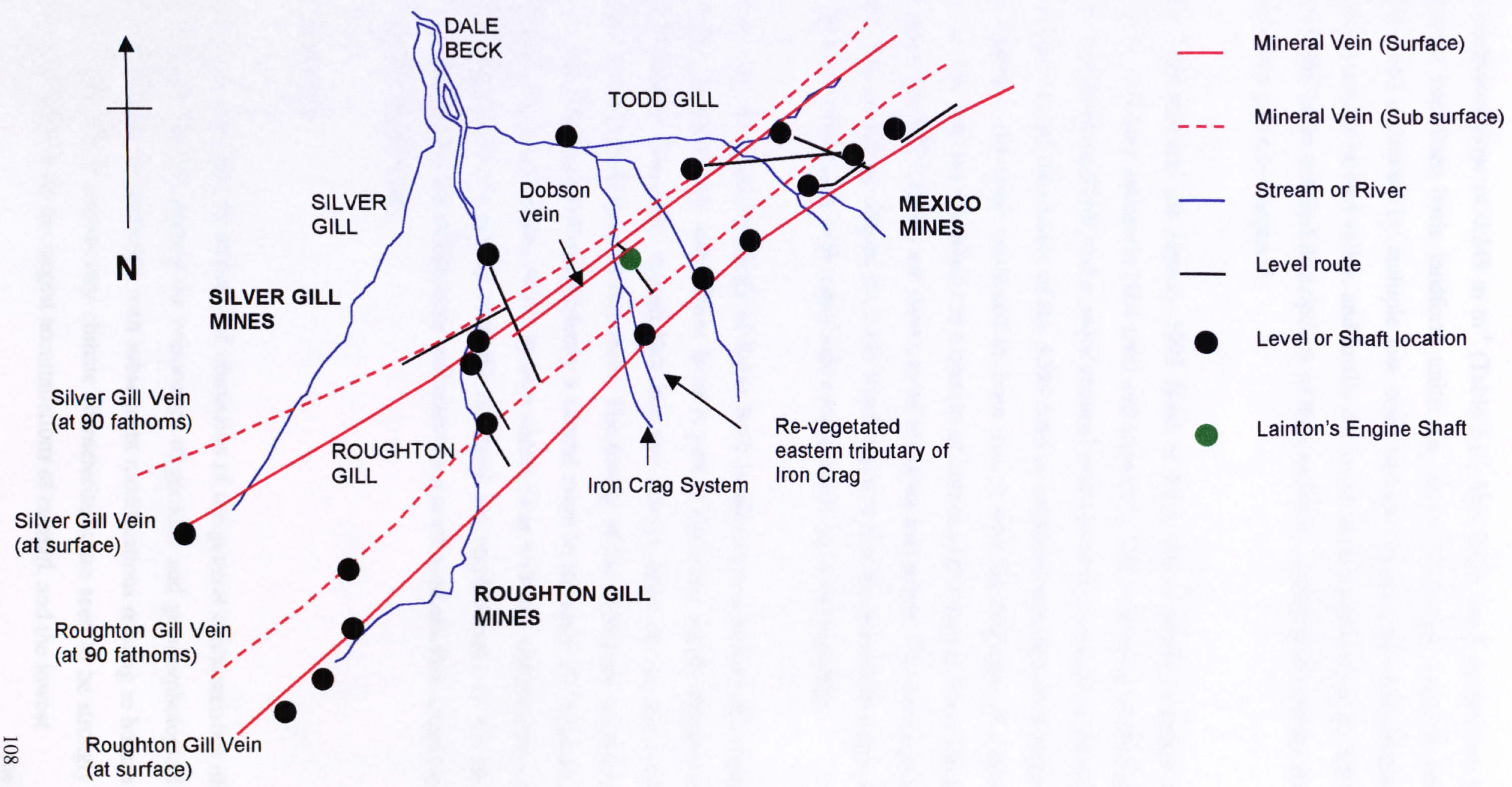
Mining activity focussed on two main mineral veins called the Silver Gill vein and the Roughton Gill vein, both of which cut across the Iron Crag system (Figure 3.18b). These were worked from sub-surface levels largely from the west i.e. Roughton Gill (Adams, 1988). It was not until later that direct disturbance occurred towards the east of the valley head, i.e. around Iron Crag. The impacts of the disturbance appear to be limited. Most noticeable are a series of tracks and drainage leats traversing the hillside at different elevations. A platform above the fan apex (Figure 3.16, 3.19), is earth works associated with the construction of Lainton's Engine Shaft. This was built for the Caldbeck Fells Consolidated Lead and Copper Mining Company Ltd. between 1866 and 1870, to de-water the proposed workings at Mexico Mine and also provided access to the Dobson vein (Adams, 1988; Cooper and Stanley, 1990) (Figure 3.19). Therefore disturbance of the Iron Crag system is likely to have included the construction of the engine shaft, the delivery of the steam engine, the supply of water and coal to power the engine, and the pumped mine water from the shaft up to 1870.

An interesting question is whether the Iron Crag system existed prior to the 19th Century mining. This is questioned as historical maps of the area fail to show any stream system beneath Iron Crag (Burley, 1819; and Ordnance Survey, 1865). This omission is considered a result of selective cartography as a plan of the mines (Anon. 1823) clearly shows Iron Crag and the easterly tributary. Field observations suggest the mining activity around Lainton's shaft cuts across the fan and channel, indicating that the Iron Crag system pre-dated this intervention. Chapter 6 discusses this issue and shows fan deposition to be at least 2000 years old.

3.2.3 Raise Beck torrent, Helvellyn massif

Raise Beck (NY 330 118) is a mountain torrent dominated by fluvial processes. It is in the Central Lake District Fells, 3 km south west of Helvellyn, and about 4 km north west of the village of Grasmere (NY 337 076) (Figure 3.11). It has an area of 133 ha, and has an altitudinal difference of 623 m (858 m O.D. to 235 m O.D.) and a

Figure 3.19: Plan of mining activity at the head of the Dale Beck valley (Adapted from Adams, 1988). (1 fathom = 6ft or 1.83m)



mean catchment slope of 0.249 m m^{-1} (Table 3.6). The Raise Beck system can be categorised into three basic landform units: the upper catchment which is peat moorland and is drained by multiple low order surface streams; the main channel enclosed in a steep incised valley, and finally the lower catchment fan near the A591 (Figure 3.20). More detailed descriptions of the catchment, underlying geology and vegetation are given in Chapter 7.

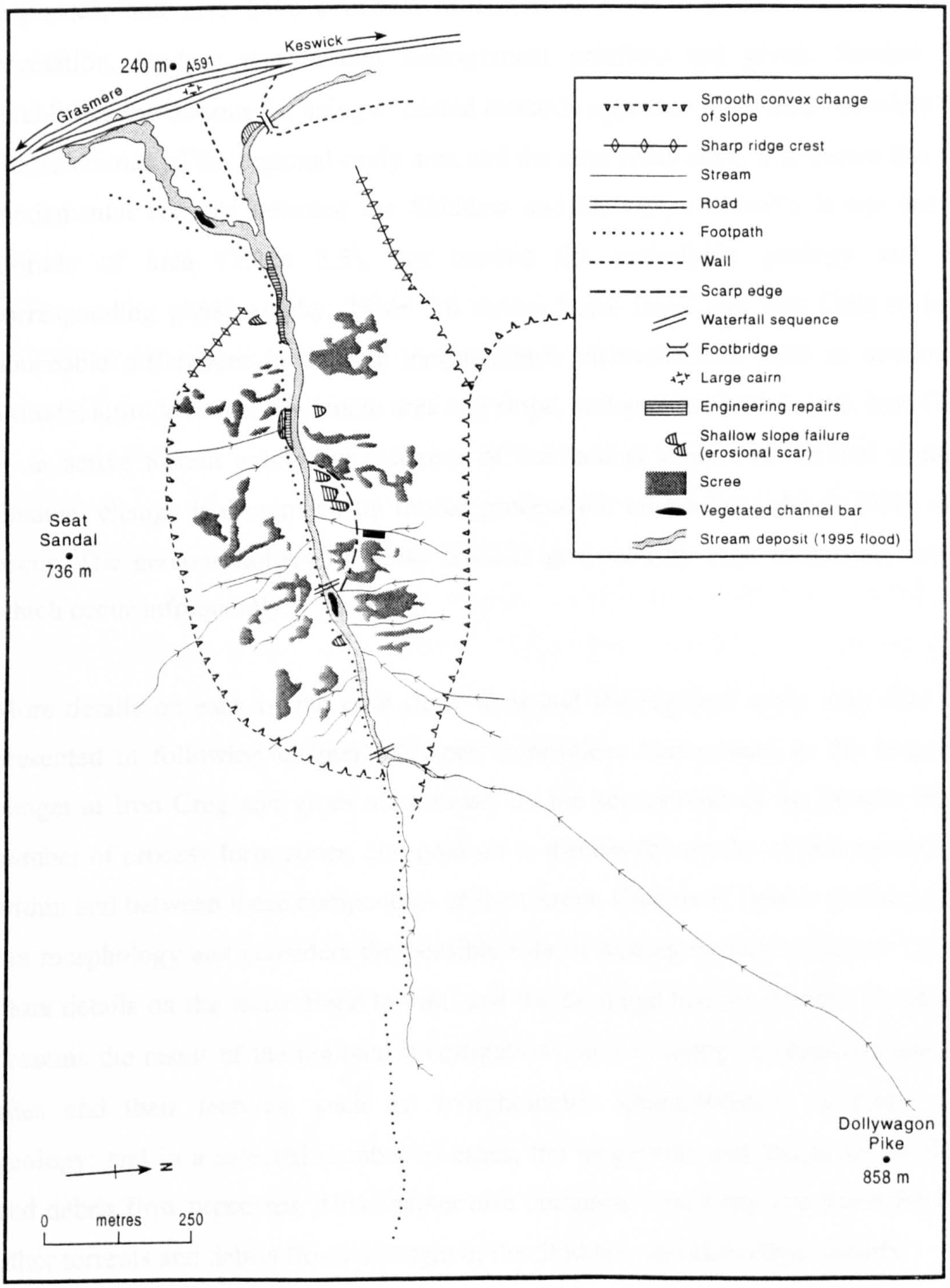
Chapter 7 reconstructs the January 1995 flood at Raise Beck, which occurred in response to a 24-hour rainstorm (164 mm) and snowmelt. The reworking of channel deposits, a shallow landslide and a major channel avulsion at the fan apex occurred. The avulsion caused the closure of the A591 road as sediment was deposited across the carriageway, and water continued to drain over it with the blockage of a sub-surface culvert. This flood is placed in a context of historical flooding at Raise Beck, two events in the 19^{th} Century are shown to be of higher magnitude. The persistence of palaeo flood evidence despite the 1995 flood suggests that the geomorphology of Raise Beck is controlled by high magnitude events which occur infrequently.

Like Iron Crag, the geomorphology of Raise Beck is subject to a history of human intervention. As previously noted Raise Beck is part of the water supply catchment for the Thirlmere Reservoir, though this has not always been so, as the beck historically flowed south towards Grasmere. The timing of the northward diversion is not precisely known, but it was probably a natural event in the early 20^{th} Century. Noticeable human modification of the system comes later with the stabilisation of the channel banks, which mostly recently involved the emplacement of rip rap boulders to stabilise the toe of hillslopes and reinstate a northward channel following the 1995 flood (Figure 3.20).

3.3 Conclusion

This chapter has provided an outline and discussion of the general characteristics of the English Lake District, namely the importance of geology and geomorphological processes in forming the landscape with subsequent modifications relating to human land use changes. The contemporary climate characteristics are seen to be strongly influenced by altitude, with the largest accumulations of rainfall, and the lowest

Figure 3.20: Geomorphological map of Raise Beck, derived from aerial photography and field reconnaissance



mean temperatures being generally observed at higher altitude, where a freeze-thaw climate prevails during the winter (Manley, 1973). Drainage of the Lake District, has been classically described as 'radial' and 'superimposed on a former rock dome', these assertions are questions by Clark (1988). Generally the drainage consists of many small and steep streams which like other upland locations exhibit flashy runoff responses, and also have evidence of historical flood events. Details of soils, vegetation, landuse and current management practices are given. Section 3.2 establishes the reasons for using a 'nested research approach', and also considers the characteristics of the regional study area and the case study sites. It is shown that the fundamental contrast between the Skiddaw and Helvellyn massif's is not one of altitude or area (Table 3.5), but instead the underlying geology and the corresponding physiography. Table 3.6 shows Raise Beck and Iron Crag to have noticeable differences in the site morphometric characteristics such as maximum altitude, altitude range, catchment area and slope, and aspect. Furthermore, Iron Crag is an active torrent exhibiting evidence of continuous slope and channel change. Channel change is dominated by fluvial process but channelised debris flows also occur. The geomorphology of Raise Beck is governed by high magnitude events which occur infrequently.

More details on each of the case study sites and the regional study area sites are presented in following chapters. Chapter 5 provides background to the sediment budget at Iron Crag and gives more detail on the segregation of the system into a number of process-form zones, and goes on to discuss the results of process activity within and between these components of the torrent. Chapter 6, details the Iron Crag fan morphology and considers the possible role of mining impacts. Chapter 7 gives more details on the Raise Beck torrent, and the drainage history. Finally Chapter 8, presents the result of the regional investigations, and in doing so identifies specific sites and their features, such as: morphometric characteristics; relations with geology; and in a selected number of cases, the magnitude and frequency of flood and debris flow processes. This chapter also compares Iron Crag and Raise Beck to other torrents and debris flows throughout the Skiddaw and Helvellyn massifs.

CHAPTER 4: IRON CRAG CONTEMPORARY PROCESS SEDIMENTOLOGY

4.0 Scope of chapter

This chapter investigates the impact of different processes on the sedimentological characteristics of sediment mobilised (trapped) during the sediment budget monitoring period. Section 4.1 provides a brief background to particle size analysis, and how it is used to identify particular process activity. Section 4.2 outlines the aims and objectives of the chapter. Section 4.3 considers the particular methods of particle size analysis used at Iron Crag, focussing on the collection of sediment, the analysis and the interpretation of the data. Together sections 4.1 and 4.3 provide the background for the main results of this chapter which are contained in the section 4.4. Section 4.4 is composed of three main elements. First, the relation of particle size to process activity is evaluated. Secondly, the dominant phases of process activity in the various measurement intervals are classified on the basis of meteorological data and field observations. Third, using graphical statistics of particle size, the impact of process activity on sediment sorting is investigated. Secondary influences such as instrument type, sediment sources and seasonality are also considered. Finally, section 4.5 provides a conclusion and a synthesis of the findings, and recommendations for improvements are given.

4.1 Background

In discussions of particle characteristics certain properties are often used to describe sediments. These include size, shape, and surface morphology (Friedman and Sanders, 1978; Briggs, 1981; Leeder, 1982; Chamley, 1990; Whalley, 1990; Davis, 1992; Boggs, 1995; Nichols, 1999). In the analysis that follows emphasis is given to particle size. Gale and Hoare (1991) state that particle size can be expressed in terms of linear dimension, volume diameter and hydraulic equivalent diameter. Davis (1992) notes that the volume of an individual particle is easily obtained and is independent of shape. However, the measurement of the volume of a large number of particles is difficult and time consuming, as each particle requires individual measurement. Therefore, linear measurements of particle size are more common, even though particle shape is infinitely variable (Leeder, 1982; Davis, 1992). In geomorphology one of the three particle axes, commonly the intermediate (b-axis) is used.

Friedman and Sanders (1978, p63) state that particle size is important in several ways. Firstly, different sized particles originate from different rocks and sediment sources. Secondly, size is an indicator of resistance of a particle to weathering and erosion. Thirdly, size can often be used to interpret the processes of transport and deposition. The use of particle size characteristics to investigate process(es) of particle transport and deposition in both contemporary and palaeo environments has been widely performed (for example- Greenwood, 1969; Visher, 1969; Statham, 1979; Briggs, 1981; Leeder, 1982; Gale and Hoare 1991; Boggs, 1995; Reid and Dunne, 1996; Nichols, 1999). However, Ehrlich (1983) and Gale and Hoare (1991) point out that despite extensive efforts by sedimentologists to associate grain-size characteristics with particular sedimentary environments, and thus process, the results have often been confused and contradictory. Gale and Hoare (1991) explain that this uncertainty stems from the complexity of the processes responsible for sediment transport; differing lithology and mineralogy of the material involved; and the role of sediment sources in influencing the particle size distribution.

Except for aeolian deposition, production of source material on hillslopes generally results from the weathering of underlying soil and bedrock (Selby, 1993; Reid and Dunne, 1996). The combination of weathering type (i.e. physical, chemical or biological) and the physical and chemical composition of the rock, collectively determine the particle size characteristics of the material produced (Gale and Hoare, 1991). After the initial formation of the hillslope regolith, displacement of the material from the in-situ position creates colluvium. Martz and Li (1997, p 20) state that the processes of erosion and deposition creating colluvium alters the grain size distribution of the hillslope sediment, especially at the surface due to material segregation during transport. Gale and Hoare (1991) also suggest that soil formation processes (pedogenesis) alter the particle size distribution of the surface sediment. Given the assumption that the surface particle size distribution of a source material is a function of both the parent material (regolith) and modifications to the regolith after its formation, it is reasonable to expect spatial and temporal variability in the initial sediment signature of hillslope material. However despite these complexities Gale and Hoare (1991) state that it is still possible to make generalisations about the particle size characteristics associated with different processes. It is on this basis that this study proceeds, and hypotheses concerning the particle size distributions and different processes are discussed later.

4.2 Aims and objectives

The overall aim of this chapter is to examine the particle size characteristics of sediments collected by Gerlach troughs and nets (see Appendix 5.1: 2,5 for instrument design details, and section 5.1.2 for a fuller discussion of their usage) during the sediment budget monitoring period (defined in section 5.2.1.1) and relate these to the dominant processes operating during the various measurement intervals (defined in section 4.4.3). This approach seems feasible given that field observations at Iron Crag suggest different processes erode different grades of sediment from the hillslope at different times. The objectives are:

1) To identify the impact of different processes on the particle size distribution of trapped sediments.
2) To determine the variability in particle size distributions as a function of hillslope sediment sources, seasonality and the type of trapping instrument.

4.3 Methodological considerations

This section considers particle size analysis of Iron Crag sediments obtained by Gerlach troughs and nets during the sediment budget monitoring period (see chapter 5 for instrument and monitoring details). The collection of sediment; methods of particle size measurement; and the analysis of the particle size data are discussed. These are important considerations before the significance of contemporary sedimentology can be interpreted.

4.3.1 Collection of sediment

Sediment collected for particle size analysis has to be representative of the environment from which it was collected otherwise subsequent analyses will be a misrepresentation of reality (Richards, 1990). Gale and Hoare (1991) state that determining an adequate sample size is difficult, as this will be a function of both the size of the largest clasts and the particle size distribution. Standards published by several organisations: American Society for testing and materials (1987), British Standards Institution (1977, 1985), and The International Organisation for Standardisation (1978)) purport to indicate the minimum size of sample required to achieve representative particle size distributions. For example, the British Standards Institution (1977, 1985) schemes (BS 1377: 1975; BS 812/ 103.1: 1985) indicate that if the maximum particle size is 63 mm then the minimum mass of sample required is 50 kg (Table 4.1). The particle size value is the largest particle size accounting for at least 10 % by mass of the sample particle size distribution. The mass of the sediment collected at Iron Crag (samples 1-5 kg) is often much less than these recommended minimum sample sizes. However, because sample sizes are determined by process rates and the capacity of individual sediment traps, they represent the best available estimates of particle size transported during a given measurement interval. This sampling constraint should be borne in mind when the results of the particle size analysis are discussed.

Table 4.1: Minimum quantities of sediment required for particle size analysis, based on British Standard BS 1377: 1975/ BS 812: Part 103.1: 1985. Where significant constitutes the largest particle size accounting for at least 10% of the sample mass.

Maximum size of material present in a significant proportion (mm)	Minimum mass of dry Sample required for sieving (kg)
75	70
63	50
50	35
40	15
28	5
20	2
14	1
10	0.5
6	0.2
5	0.2
3	0.2
<3	0.1

4.3.2 Laboratory measurement of particle size

Following field sampling sediment is transferred to refrigerators for storage until it is required for laboratory analysis. Laboratory routines for sediments trapped by Gerlach troughs and nets are given in Appendix 4.1. Particle size is measured with sieves and calibre plates. Sieved sediment is measured at half phi intervals ranging between – 4 ϕ to 4 ϕ. Sediment coarser than –3.5 ϕ is passed through calibre plates (metal plates with different hole sizes corresponding to half phi intervals).

4.3.3 Analysis of particle size data

Boggs (1995) states that particle size analysis generates a large amount of data that must be simplified before it can be interpreted. Graphical plots are a common means of data reduction. For particle size analysis three types of graph are widely used (for example see Leeder, 1982 and Nichols, 1999) i.e. a histogram, a frequency curve and a cumulative frequency curve. McManus (1988) indicates that geologists usually calculate the cumulative percentage coarser than a given particle size, and thus a high value of cumulative percent corresponds to the finer sediment. This study adopts the reverse, i.e. percentage finer, which is commonly used in civil engineering and geomorphology (McManus, 1988). McManus (1988), and Boggs (1995) point out whilst graphical plots provide a means of quick inspection of particle size characteristics, they are of little use for comparison with large numbers of samples, where consistent and accurate analysis is required. A more suitable approach is to conduct statistical analyses on the data. It is often assumed that the particle size distributions of natural sediments (measured on the phi scale) approach a normal distribution when plotted as a frequency curve (Krumbein and Pettijohn, 1938; Briggs, 1981; Davis, 1992). However, Friedman and Sanders (1978); Leeder (1982); McManus (1988); and Boggs (1995) state that most particle size distributions deviate from log-normality, and at best only approximate log-normality. It is these deviations that characterise particular sediments and allow specific processes to be identified (Boggs, 1995). Two forms of statistical analysis have been developed to consider these deviations, i.e. graphical methods and moment methods.

Graphical methods use percentile values of phi size derived from cumulative frequency curves. These values are used to calculate mean, standard deviation, skewness and kurtosis of the sample (see equations 4.1 to 4.4) (Folk 1974; and Friedman and Sanders, 1978).

Graphical Mean

$$M_z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \quad \text{(Equation 4.1)}$$

Inclusive graphical standard deviation

$$\sigma_i = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \quad \text{(Equation 4.2)}$$

Inclusive graphical Skewness

$$SK_i = \frac{(\phi_{84} + \phi_{16} - 2\phi_{50})}{2(\phi_{84} - \phi_{16})} + \frac{(\phi_{95} + \phi_5 - 2\phi_{50})}{2(\phi_{95} - \phi_5)} \quad \text{(Equation 4.3)}$$

Graphical Kurtosis

$$K_G = \frac{(\phi_{95} - \phi_5)}{2.44(\phi_{75} - \phi_{25})} \quad \text{(Equation 4.4)}$$

The graphical mean approximates the arithmetic average of all the particle sizes in a distribution. The inclusive graphical standard deviation or sorting is a measure of the range of particle sizes. Skewness considers the extent of asymmetry in a distribution, specifically the tails of the distribution, which are dominated by the largest and smallest particles. The final statistic is kurtosis, which is a measure of how sharp or peaked the grain size distribution is. Chamley (1990), Davis (1992) and Nichols (1999) indicate that these statistics can be taken to be indicative of different process attributes. Mean size is an expression of the transporting force causing the motion of certain sediment (competence). Standard deviation or sorting provides an appreciation of the size grading processes active during transport (see Costa, 1984, 1988), and is therefore an indicator of the process type. Skewness reflects the preferential transport of certain grades of material. Kurtosis provides a means of further characterising the sediment population of a sample.

Alternatively Gale and Hoare (1991) advocate the analysis of depositional environments using bi-variate scattergrams of graphical descriptive statistics, and the use of CM diagrams. A CM diagram is again a bi-variate plot but not one based on the summary statistics, but instead on the relationship between D_{99} (99% of the distribution is finer or 1% is coarser) and the D_{50} (median percentile). Other approaches are also outlined by Gale and Hoare (1991) including truncated log normal sub-populations (e.g. Visher, 1969) and multivariate statistical techniques.

The four descriptive statistics of a particle size distribution can also be calculated by the method of moments that utilise the entire particle size distribution, as developed by Krumbein and Pettijohn (1938). For a detailed discussion of this method consult Friedman and Sanders (1978) and McManus (1988). McManus (1988, p79) states:

"It should be stressed that, because all grains are used, this form of analysis should not be used unless the size distribution is fully known. Distribution of the 'pan residue' fraction from sieving among a specified number of phi classes 'to permit application of moment methods' is not good practice and may lead to misleading, if not meaningless, results being obtained. If a total of less than 1% of the population is undefined then the errors are unlikely to be great, but the reliability of the moment decreases sharply as the proportions of undefined materials increases...."

In the case of the Iron Crag sediment the pan residue proportion often exceeds the 1% threshold, given a significant contribution of finer particles. Therefore following McManus (1988) moment methods cannot be strictly applied to Iron Crag sediments. With these limitations in mind Iron Crag sediments are analysed using the graphical log-normal approach. This approach is relatively simple, has been more extensively applied in a variety of environments, and is relatively robust when dealing with significant pan residues.

4.4 Contemporary sedimentological variability

Factors governing the particle size distributions of sediments transported at Iron Crag are investigated by comparing 'hypothesised' and 'actual' particle size characteristics associated with different process regimes. The hypothesised impacts of various processes are established from a review of published literature concerning the erosion of sediment from hillslopes (Section 4.4.1) and other contributing factors (Section 4.4.2). The dominant processes operating during each measurement interval are determined from field observations and meteorological records (Section 4.4.3).

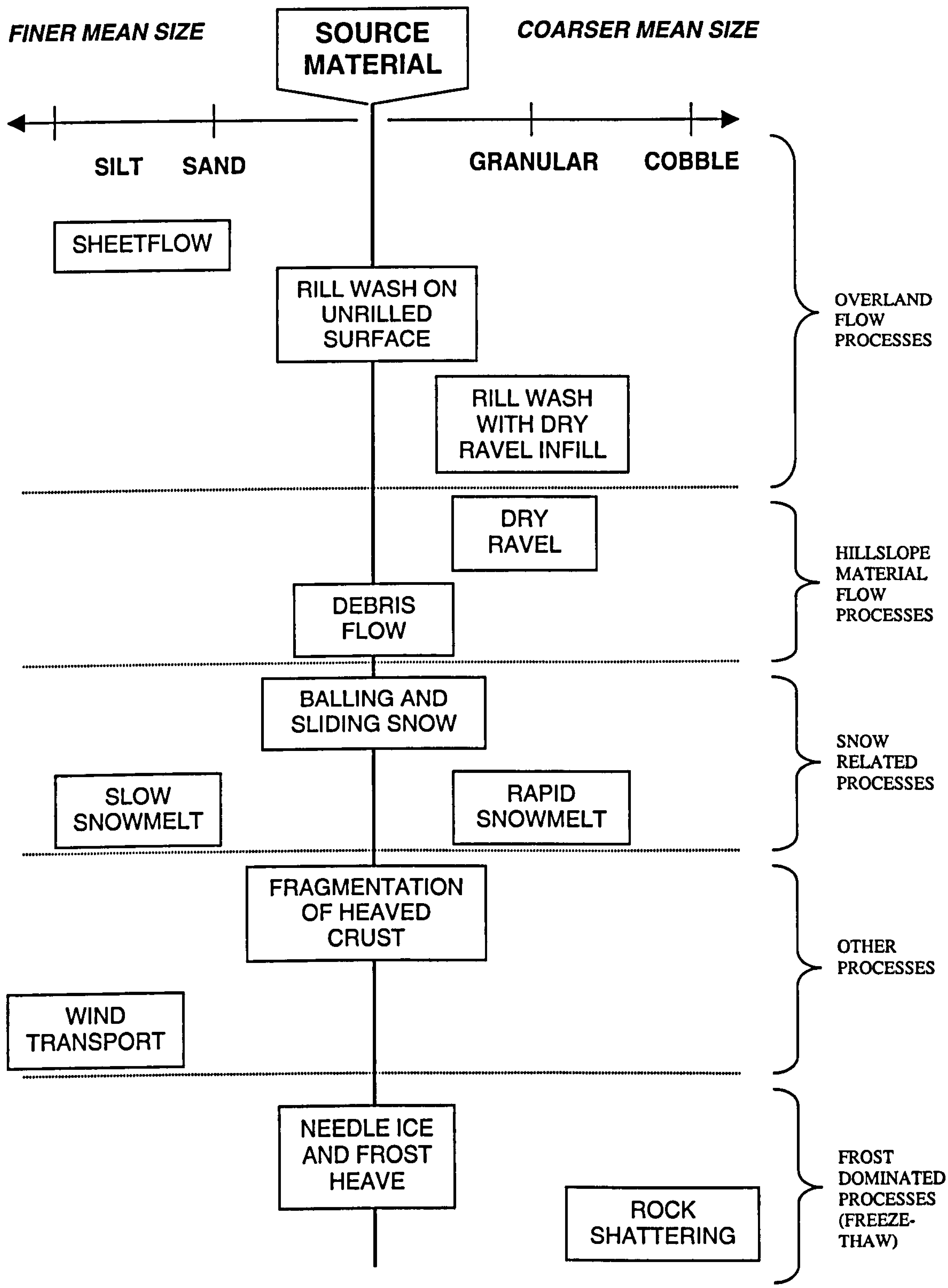
4.4.1 Hypothesised particle size distributions

Statham (1979), Briggs (1981), Reid & Dunne (1996), and Nichols (1999) state that different erosion/ transport processes will transport different particle size fractions of a given material, i.e. they have differential entrainment and sorting abilities. Thus the sediment signature of the hillslope sediment collected by the Gerlach troughs and the nets should reflect variability resulting from the dominance of different processes. The physical processes causing the detachment and transport of material on the hillslopes at Iron Crag were identified in the planning phase of the sediment budget (as reported in Chapter 5), and were subsequently confirmed by field observation. The impact of each of these processes on the particle size distribution is hypothesised in Figure 4.1. This diagram indicates whether a process will transport sediment that is finer or coarser than the original sediment. As shown some processes do not exhibit preferential sorting but instead transport the original sediment *en masse*. This diagram is based on several assumptions for each process which will now be discussed.

4.4.1.1 Sheetflow

Hogg (1982), in a hydrological and geomorphological classification of overland flow processes, defines sheetflow as a high-frequency low-magnitude flow of water in a continuous laminar unconcentrated sheet. Turbulence can be created from raindrop splash (Evans, 1980) and the flow can become divided due to irregularities such as topographic variation and vegetation (Emmett, 1970, 1978; Thornes, 1980,

Figure 4.1: Sediment sorting potential of geomorphic processes operating at Iron Crag during the sediment budget monitoring period.



Gertis *et al.*, 1990). Given that the transport of particles is governed by the relationship between the size of a particle (resistance) and the power of flowing water (Briggs, 1981), it is likely that only finer particles will be transported by sheetflow (Thornes, 1980; Reid and Dunne, 1996). This is because sheetflows have low transport velocities and the flow has a laminar velocity profile. However as Morgan (1995) suggests the very finest particles are resistant to flow because of their cohesiveness i.e. micro-aggregation (Gertis *et al.*, 1990) and the least resistant particles are silts and fine sands. Evans (1980) similarly states that it is the sand fraction that is most erodible. However it is conceivable that even the finest material will be transported in the form of aggregates (Kirkby, 1980).

4.4.1.2 Rill wash

Rills are a channelised form of turbulent overland flow, where the flow is concentrated into micro channels on the hillslope surface (Hogg, 1982; Selby, 1993; Summerfield, 1994; Morgan, 1995, Reid and Dunne, 1996; Gatto, 2000). They are formed by incision of the flow at higher velocities (Evans, 1980). Higher velocities result from increasing slope gradient; increased rainfall intensity; or because surface storage is exceeded (Evans, 1980).

It is often reported that rill flows are more erosive than inter-rill (sheet) flows, because of their greater velocity and turbulence (Foster *et al.*, 1984; Gilley *et al.*, 1990). The implication of this is that rill flows are largely non-selective with regard to the particle size transported, so that all particles including some coarse particles are transported (Govers, 1985; Poesen, 1987; Morgan, 1995). Therefore it is likely that the particle size distribution produced by rill erosion on a previously unrilled surface will reflect the distribution of the available sediment, excluding only the largest rock fragments. However, as some rills are more permanent features on a hillslope the sediment they transport will be a function of that supplied to the rill by other processes (Morgan, 1995). Convergence of inter-rill erosion (Selby, 1993; Morgan, 1995), weathering of the rill bed and walls (Morgan, 1995; Gatto, 2000), and infill by dry ravel (Reid and Dunne, 1996) will result in a complex sediment signature.

4.4.1.3 Dry Ravel

Sidle *et al.* (1993) define dry ravel as a gravity-driven erosion process, which contributes to soil loss on disturbed sites. It causes coarse, cohesionless material to move down steep slopes. Ravel is produced by the weathering of coarse fragments, destabilisation of regolith, and the differential erosion of fines leaving a coarser layer of material in situ (Statham, 1979). Reid and Dunne (1996) state that the highest rates of ravel formation occur following freezing and thawing and wetting and drying.

4.4.1.4 Debris Flow

Varnes (1978) states that a debris flow is a rapid mass movement of a body of granular solids, water and air. Debris flows may be generated from a shallow slide on a hillslope, where the slide is caused by excess soil moisture. Costa (1984) notes that slope failures can transform into debris flows, possibly by several mechanisms including dilatancy (increase in bulk volume of a material) associated with incorporation of additional water or by liquefaction. The particle size distribution of a debris flow deposit therefore reflects the material involved in the initial slope failure and further changes resulting from the viscous flow process. Statham (1979), Briggs (1981), and Reid and Dunne (1996) all suggest that mass-movements displace the entire soil column and produce poorly sorted sediments. Thus the particle size distribution of a shallow slide will closely reflect that of the hillslope material. Furthermore because debris flows move as a single body of material at the same velocity, little separation of the particles and water occurs during transport (Costa, 1988). Thus the particle size distribution of the original sediment is maintained. The only modification that can occur is from the input of further sediment by erosion during transport. Erosion does not always occur, as debris flows have been observed to flow over grass and smooth fan surfaces without causing any erosion (Johnson and Rodine, 1984; Selby, 1993). Therefore debris flows will tend to transport particle size distributions very similar to the hillslope material.

4.4.1.5 Wet snow movement processes

Wet snow has been observed to fail on slopes in the form of wet snow slides/ avalanches (Gardner, 1983); slush flows (Washburn and Goldthwaite, 1958; Nobles, 1966; Elder and Kattelman, 1993) and by wet snow balling which can occur in conjunction with wet snow avalanching (Fraser, 1966; Gardner, 1970). These processes entrain, transport and deposit material on slopes (Rapp, 1960; Caine, 1969; Luckman, 1977, 1978). Wet snow avalanches and snow balling have been observed at Iron Crag. On the basis of observation in the Lake Louise area of the Canadian Rockies, Gardner (1970, 1983) states that wet cohesive snow balls incorporate unconsolidated material, though particle sizes involved are not specified. Ackroyd (1986) considers the sediment size distribution of avalanche transported material in the Torlesse Range of New Zealand's Southern Alps, which was found to be similar to the talus material from which it is derived. On the basis of this limited evidence it is assumed that the particle size distribution of sediment transported by wet snow processes will closely reflect the underlying surface material, and that little preferential sorting will occur. However, it is speculated that in the case of snow balling the size of the snow ball; the softness and cohesion of the snow (Gardner, 1983); the extent to which the underlying ground is frozen (Gardner, 1983); and the extent of the snow cover removed by the rolling snow may cause sediment sorting.

Snowmelt has several implications for sediment transport. Ward and Robinson (1990) state that before snowmelt occurs a metamorphosis of the snowpack must take place, which alters the properties of the snow. Dry freshly fallen snow is characterised by sharply defined edges (Speer *et al.,* 1996). The processes of metamorphism causes crystals to become more rounded eventually forming coarse ice crystals. Accompanying this change is an increase in snowpack density; temperature and water content (Dingman, 1994). The snow is said to be ripe, as any further inputs of energy will result in the output of melt water (Dingman, 1994). Therefore the rate of the snowmelt is controlled by the rate of energy exchange between the snowpack and its environment (Ward and Robinson, 1990). Wade and Kirkbride (1998) in a study of snowmelt induced soil erosion in Scotland, conclude that the rate of runoff generation is a significant factor, as the erosivity of the runoff will increase with the rapidity of the thaw. Where thaw was rapid and the underlying ground saturated, significant rilling occurred. Conversely where thaw was slower and the underlying ground was previously frozen, rilling was limited in extent and surface wash erosion processes dominated. Given these observations it is seems that both concentrated and unconcentrated overland flow can be generated, and the size of sediment transported is assumed to be similar to that mobilised by sheetwash and rilling.

4.4.1.6 Fragmentation of heaved crust

Farres (1978) defines a crust to be a continuous particle cover with no definable aggregate boundaries. Valetin and Bresson (1998) define a crust to be a soil surface with reduced porosity and high penetration resistance. Field observations on the hillslopes at Iron Crag indicate that under certain conditions a widespread crust can form. For example, following a freeze-thaw cycle in April 1999, the heaved material was transformed into a crust (Meentemeyer and Zippin, 1981). It is assumed that the particle size distribution of the fragmented crust will be very similar to that produced by heave (i.e. similar to the parent material- see section 4.4.1.8). However in the process of break down some slight sorting may occur. For example dry fines would be susceptible to removal by wind action, and larger fragments may travel further under the influence of gravity.

4.4.1.7 Wind transport

Wilson and Cooke (1980) state that wind erosion is the process by which loose sediment is picked up and transported by the wind, and surface material is abraded by windborne particles. It is widely reported that wind erosion removes fine material (e.g. Bagnold, 1941; Visher, 1969; Wilson and Cooke, 1980), which leaves a coarse lag deposit (Wilson and Cooke, 1980). Therefore the particle size distribution of a wind deposited sediment would be well sorted and be dominated by finer particles.

4.4.1.8 Frost heave and freeze-thaw processes

The effect of freeze-thaw is considered with regard to heave of hillslope sediment and the frost shattering of exposed rockfaces. Frost heave is the vertical movement of material due to the formation of ice (Summerfield, 1994). French (1996) states that two distinct forms of ice can form in a freezing soil, i.e. segregation ice and pore ice. Segregation ice is where ice lenses form at or near the surface, resulting from the migration of water to the freezing front due to thermal gradients and suction gradients (Meentemeyer and Zippin, 1981; French, 1996). Pore ice is where the freezing level descends into the soil in the absence of a sufficient supply of moisture, thereby freezing pore water and sediment in-situ.

A particular form of segregation ice is called needle ice. This consists of fine filaments of ice growing orthogonal to the surface rather than parallel to it (Outcalt, 1971; Washburn, 1979; Meentemeyer and Zippin, 1981; Lawler, 1988; Branson *et al.*, 1996). Hay (1936, 1943), with reference to the Lake District, states that needle ice has been observed to create an entirely false surface of gravel on footpaths and remove many stones from river banks, all of which is deposited upon the melting of the ice. Though of importance here is the particle size distribution of sediment incorporated into the needle ice, as this is transported by gravity upon the melting of the needle ice. In this regard Lawler (1988, p 138) states that needle ice can move both fine and coarse material in a selective and preferential way, as evidenced by the landforms and patterns which result, e.g. sorted stone stripes. Contrary to this, Meentemeyer and Zippin (1981, p124) investigated the selectivity of sediment lifting by needle ice in soils under laboratory conditions. They found the cumulative percentage curves for soil residue deposited by melted needle ice to be near identical to the curves from the parent material. They acknowledge that needle ice can create sorted forms, but suggest this is a function of the settling process not the lifting process.

The frost susceptibility of a soil partly determines whether segregated ice forms (French, 1996). Fine-grained soils are frost susceptible because they have small pores which allow cryosuction (supply of water to freezing plane) to be more easily maintained. However, where pore connectivity is not perfectly maintained the freezing front may descend and pore ice can form which incorporates sediment between two layers of needle ice (Branson *et al.*, 1996). The descending freezing front incorporates different sediment sizes than would normally be expected by needle ice formation at or just below the surface. This is based on the assumption that the particle size distribution will alter with depth, due to the changing distance from the weathered parent material (Selby, 1993) and different processes acting at the surface (Martz and Li, 1997). It is concluded that needle ice and frost heave tend to displace the available soil material with little size sorting.

Rockfalls tend to occur following thawing of the bedrock, fractured during diurnal and/ or seasonal freezing (French, 1996). Detailed discussions of these processes are provided by Couthard and Francou, 1989; Matsuoka, 1990; Matsuoka *et al.*, 1997; and, Matsuoka and Sakai, 1999. The particle size distribution of sediment produced by diurnal freeze-thaw activity rarely includes cobbles and boulders (Matsuoka and Sakai, 1999). Diurnal freeze-thaw action does not penetrate deeply into the rock to release large slabs. Matsuoka and Sakai (1999, p313) suggest:

"One of the significant parameters affecting the size of rockfall debris is joint spacing, because a rock enclosed by intercrossing joints tends to be detached from the rockwall."

Similarly Couthard and Francou (1989) state that frost wedging of blocks along macro fissures is the main process of detachment at their study sites in the French Alps. Further changes in the size of rockfall debris may result from post failure modification, such as splitting of debris during transport. Therefore freeze-thaw and other rockfall weathering processes are likely to produce clasts reflecting the local joint spacing and modifications following the initial rock detachment. Field observations at Iron Crag indicate that gravel and cobble sized fragments are collected by nets below active crags (Figure 4.1).

4.4.2 Other variables affecting the particle size distribution of sediments collected

In addition to the parent material and the erosional process controls, several other variables influence the particle size distribution of the sediment collected by the Gerlach troughs and nets. These include the sampling efficiencies of instruments; the positioning of instruments; the influence of discrete process events; and interference by animals. These factors are now taken into consideration.

4.4.2.1 Sampling efficiency of instruments

The ability of an instrument to collect sediment is determined by its sampling efficiency. Any deviation from the installation setup alters the ability to collect sediment efficiently. In the worst scenario instruments fail and collect no sediment. Nets and Gerlach troughs are used in the sediment budget to collect sediment from different processes. Gerlach troughs collect sediment from on-slope processes (sheetwash, rainsplash, dry ravel, soil creep, wind, and needle ice collapse) and intercept small debris flows, rill flow, and wet snow processes. Nets collect rockfall fragments from crags and the hillslope. Despite their design some overlap of process monitoring occurs. For example nets occasionally collect sediment from on-slope processes. In such cases the trapped particle size distribution is conditioned by the 10 mm mesh size of the nets. Given that this sampling efficiency is low, nets collecting sediment from on-slope processes are removed in the final analysis of the deposits. Similarly the size of the aperture between the aluminum plates at the front of the Gerlach trough (≅ 46 mm) limits the maximum size of sediment collected, and thus excludes some of the larger fragments associated with rock shattering processes. This is acceptable as Gerlach troughs are not designed to monitor material from this process.

4.4.2.2 Additional considerations

The siting of an instrument is important in determining how well it collects sediments. This effect is most noticeable with regard to the positioning of nets. Nets positioned directly beneath crags collect material largely from rockfall. However those positioned away from the base of crags (on slopes) also collected material from other processes. Additionally, only the larger fragments of rockfall material are collected in these locations because under the influence of gravity larger fragments travel further downslope than finer material (Statham and Francis, 1986; Govers and Poesen, 1998). However the effect of distance on sediment size is difficult to quantify, without knowing the variability in the size of the material produced from local rockfaces.

Reid and Dunne (1996) state that discrete processes are those which are infrequent and are of large magnitude. Examples include debris flows, deep rilling, and wet snow avalanches. When these processes do occur, the sediment eroded is less likely to be captured than those from frequent erosion processes, which are more widespread across the land surface (Reid and Dunne, 1996). If sediment is captured it is likely to fill a Gerlach trough quickly, this is beneficial in that it will provide a clear particle size distribution of an individual process, but is unlikely to collect all the eroded sediment.

Animals, particularly sheep, at Iron Crag have been observed to disturb instruments, and dislodge sediment. Evans (1997c, 1998) and Hall *et al.* (1999) state that animals have an indirect role in erosion by opening up the ground to geomorphic processes. More directly with regard to the particle size distribution Govers and Poesen (1998) state that sheep can cause vertical sorting of the hillslope material. Trampling causes kinetic sieving, i.e. upward movement of coarse material and the downward movement of fines. Dislodged material moving downslope will be sorted under the influence of gravity if it is a dry flow process.

4.4.3 Process activity during the sediment budget measurement intervals

Using a combination of meteorological data and field observations the dominant hillslope process activity for each sediment budget measurement interval could be characterised. Table 4.2 presents the results of the field data. This consists of information from a local tipping bucket rain gauge and the rockface temperature logger situated in the primary hillslope zone (see Appendix 5.1 for more detail). Observed changes in site morphology and evidence of specific processes are summarised in Table 4.3.

Measurement intervals refer to the period of time between emptying of sediment traps, some measurement intervals have more than one start and end date. This is because sometimes it was not possible to empty the sediment from all instruments within one day due to adverse weather conditions, e.g. snow cover and frozen ground. The remaining sediment was often collected within a few days. This complication mostly occurred between measurement intervals 1 and 4 (13^{th}

November 1998 to 7th January 1999). A longer elapsed time between measurement intervals makes the prescription of dominant process activity more difficult.

Rockface temperature- is used in preference to the ground surface temperature, as the absence of a radiation shield at the ground surface occasionally led to anomalously high ground surface temperatures. The rock face thermistor obtains some shielding from surrounding rock fragments and is thermally more stable. The rock face temperature also records rock face freeze- thaw cycles and so provides a more accurate indicator of conditions required for rock shattering. Following Matsuoka *et al.* (1997) *freeze-thaw cycles* are defined by one complete oscillation of temperature below and above zero degrees. It is acknowledged that this does not necessarily define the effective freeze-thaw cycle which causes rock shattering (Matsuoka, 1990). However, Matsuoka (1990) shows there to be no simple definition of the temperatures required for effective freeze-thaw. In the absence of instrumentation capable of measuring soil moisture and rock joint expansion, which are needed to define the effectiveness of freeze-thaw cycles, this basic definition is used.

Precipitation values represent the total sum of all tipping bucket volumes, including ice and snowmelt during a measurement interval. Snowfall is detected from the temperature data (' snow suspect' category in Table 4.2), where absence of a diurnal fluctuation in temperature is indicative of snow cover (Matsuoka and Sakai, 1999). Periods of snow and ice melt are often shown in the rainfall record as a peak in the number of tips, in combination with diurnal changes in temperature ('melt suspect' category in Table 4.2). More sustained changes in temperature, whilst capable of inducing snow and ice melt in the gauge, are generally associated with a change in the airmass with frontal weather conditions. These conditions bring rainfall that complicates the interpretation of the rain gauge accumulation record, and cannot therefore be interpreted as pure melt events.

Significant rainfall events are considered to be two or more hours of contiguous bucket tips. This definition does not include melt data, and whilst arbitrary it provides a consistent criteria for filtering out insignificant events (Table 4.4). *Rain event statistics* follow the analysis of rain event data outlined by Houghton- Carr

Table 4.2: Iron Crag monitoring summary-quantitative meteorological observations

Measurement Interval			Temperature (Rockface, °C)			No. F/T	Precipitation				Rain Event Summary								
	Dates	Number of days	Max	Min	Mean		Total (mm)	Snow Observe/ Suspect/ Melt suspect	No. Rain events	Average precipitation per day (mm)	Duration (hours)			Depth (mm)			Intensity (mm h^{-1})		
											Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
1	a.11.11.98 to 24.11.98	13	6.22	-2.44	1.53	2	59.182	0/0/1	7	4.55	16	2	7.3	23.622	0.508	7.693	3.556	0.254	1.056
1	b. 13.11.98 to 24.11.98	11	6.22	-2.44	1.12	2	30.226	0/0/0	5	2.75	15	2	6.0	10.668	0.508	5.080	3.556	0.254	0.847
2	a. 24.11.98 to 12.12.98	18	7.43	-4.82	2.61	1	90.932	0/0/0	11	5.05	14	2	5.8	25.4	0.508	7.574	6.858	0.254	1.302
2	b. 24.11.98 to 13.12.98	19	7.43	-4.82	2.66	1	97.536	0/0/0	14	5.13	14	2	6.3	25.4	0.508	6.423	6.858	0.254	1.285
3	a. 12.12.98 to 29.12.98	17	9.42	-3.85	1.90	4	101.092	1/0/0	20	5.95	8	2	4.0	20.828	0.508	4.902	7.112	0.254	1.257
3	b. 13.12.98 to 29.12.98	16	9.42	-3.85	1.93	4	94.488	1/0/0	17	5.91	8	2	4.4	20.828	0.508	5.379	7.112	0.254	1.270
4	29.12.98 to 7.1.99	9	7.43	-0.16	2.21	1	172.72	0/0/0	10	19.19	29	3	10.6	69.342	1.270	17.018	5.842	0.254	1.084
5	a.7.1.99 to 11.2.99	35	6.62	-5.81	0.54	10	165.354	2/2/1	25	4.72	19	2	4.9	33.528	0.508	5.700	6.604	0.254	1.155
5	b.7.1.99 to 14.2.99	38	6.62	-5.82	0.53	14	177.80	2/2/3	26	4.68	19	2	4.9	33.528	0.508	5.842	6.604	0.254	1.173
6	a. 11.2.99 to 10.3.99	27	6.62	-2.44	0.82	11	156.972	2/0/7	21	5.81	17	2	5.5	20.32	0.508	6.202	4.826	0.254	1.128
6	b. 14.2.99 to 10.3.99	24	6.62	-2.44	0.87	8	145.034	2/0/4	21	6.04	17	2	5.5	20.32	0.508	6.202	4.826	0.254	1.108
7	10.3.99 to 23.3.99	13	10.99	-1.97	3.33	3	80.01	0/0/0	7	6.15	21	2	8.6	25.654	0.762	11.219	4.826	0.254	1.308
8	23.3.99 to 17.4.99	25	14.09	-2.44	4.65	9	139.446	2/0/6	17	5.58	21	2	7.8	41.91	0.508	6.036	4.572	0.254	1.290
9	17.4.99 to 29.4.99	12	20.95	-3.85	5.5	5	61.214	0/0/1	6	5.10	18	4	8.5	22.86	1.016	9.440	3.81	0.254	1.111

(1. All data related to British Summer Time, GMT +1 hour, 2. MI = Measurement interval)

Table 4.2 (cont.)

Measurement Interval			Temperature (Rockface, °C)			No. F/T	Precipitation				Rain Event Summary								
	Dates	Number of days	Max	Min	Mean		Total (mm)	Snow Observe/ Suspect/ Melt suspect	No. Rain events	Average precipitation per day (mm)	Duration (hours)			Depth (mm)			Intensity (mm h^{-1})		
											Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
10	29.4.99 to 17.5.99	18	20.95	2.89	8.79	0	99.06	0/0/0	15	5.50	13	2	5.5	27.432	0.508	6.251	4.572	0.254	1.195
11	17.5.99 to 31.5.99	14	23.63	2.46	8.98	0	80.264	0/0/0	11	5.73	11	2	4.6	24.892	0.762	7.043	5.334	0.254	1.549
12	31.5.99 to 12.6.99	12	17.14	3.74	8.56	0	48.894	0/0/0	10	4.07	7	2	3.9	8.636	0.762	3.683	3.81	0.254	0.944
13	12.6.99 to 28.6.99	16	26.73	4.57	11.84	0	112.014	0/0/0	11	7.00	17	2	5.3	47.752	0.762	9.744	7.874	0.254	1.848
14	28.6.99 to 12.7.99	14	26.73	6.22	14.54	0	13.208	0/0/0	3	0.94	5	2	3.3	2.54	0.762	1.439	1.016	0.254	0.4318
15	12.7.99 to 25.7.99	13	25.17	7.43	11.89	0	113.284	0/0/0	14	8.71	17	2	6.9	18.288	0.508	7.892	4.826	0.254	1.139
16	25.7.99 to 16.8.99	22	31.93	4.99	13.46	0	42.926	0/0/0	11	1.95	11	2	4.0	6.35	0.508	2.956	3.81	0.254	0.739
17	16.8.99 to 3.9.99	18	21.33	3.74	10.83	0	49.276	0/0/0	18	2.74	7	2	3.2	11.43	0.508	2.399	4.064	0.254	0.744
18	3.9.99 to 20.9.99	17	24.01	4.57	11.29	0	112.776	0/0/0	15	6.63	9	2	4.6	30.734	0.508	7.247	8.128	0.254	1.576
19	20.9.99 to 10.10.99	20	14.85	0.29	8.11	0	161.798	0/0/0	23	8.08	17	2	6.0	31.496	0.508	6.460	6.35	0.254	1.077
20	10.10.99 to 27.10.99	17	11.38	0.73	5.96	0	44.45	0/0/0	10	2.61	8	2	4.4	9.398	0.508	3.734	4.064	0.254	0.849
21	27.10.99 to 9.11.99	13	10.6	0.29	5.8	0	186.182	0/0/0	12	14.32	28	2	9.5	62.992	1.270	15.240	8.636	0.254	1.604
22	9.11.99 to 4.12.99	25	7.83	-1.9	3.19	4	215.392	1/0/2	26	8.61	20	2	4.9	64.262	0.508	7.972	9.652	0.254	1.7272

Table 4.3: Iron Crag measurement interval (MI) summary field observations of process activity

MI	Freeze-Thaw				Snow melt		Dry/ warm conditions			Rain				Sheep trampling	Wind transport	Other observations
	Needle ice	Exfoliation	Rock fracture	Ravel	Balling up	Wet slide	Crust	Cracking	Dry Ravel	Sheetwash	Rilling	Splash marks	Debris flow			
1		*		*						*						
2		*		*									*			Debris flows in secondary zone, associated rockfall
3																F/T noted, snow covers instruments, empty before melt
4										*						Snowmelt; F/T toes washed away
5	*	*	*	*						*	*		*			Debris flow in secondary zone; Snowmelt
6			*	*	*	*					*	*				Snow slumps miss instruments
7		*	*	*							*	*				Rilling in secondary zone
8	*	*	*	*	*	*										Melt of needle ice later in day, supply material for next MI ([1])
9		*[1]					*		*							
10									*	*				*		Sheep detach blocks and create ravel flows
11									*		*			*		Rilling shown by incision of ravel cones at base of slope
12									*					*	*	Most baked heave surface gone; Wind create dry flow chutes (dry ravel)
13										*	*		*	*		Rill erosion wash into some nets; Rilling extensive, basal cones eroded Sheetwash post rilling
14									*					*		Cone aggradation
15														*		Less sheep activity; No visible slope activity
16										*	*			*		Less sheep activity; Sheetwash deposits on nets
17									*					*		More sheep activity; Cone aggradation
18											*	*				
19											*					Absence of sheep tracks
20											*			*		
21											*	*				Rilling is significant; Local cone aggradation
22	*	*	*								*					Needle ice melt removed a lot of sediment; Snow cover instruments but emptied before melt; Observe heavy rain

(1999). Storm duration is the duration of the event rainfall in hours, storm depth is the sum of the rainfall depths in each of the individual hour blocks making up the event rainfall, and intensity is the depth of rainfall per hour.

Table 4.4: Quantities of 'event' rainfall versus total measured precipitation. The proportion of collected precipitation filtered from the analysis is shown.

Date	Recorded precipitation (mm)	Total event rainfall (mm)	% loss due to melt and 2 hour + filter rule
7.1.99- 14.2.99	177.6	150.1	-15.5
14.2.99-10.3.99	145.0	131.8	-9.1
10.3.99-23.3.99	80.0	78.5	-1.9
23.3.99-17.4.99	139.4	100.6	-27.9
17.4.99- 29.4.99	61.2	56.6	-7.5
29.4.99-17.5.99	99.1	98.0	-1.0
17.5.99-31.5.99	80.3	77.5	-3.5
31.5.99-12.6.99	40.9	36.8	-9.9
12.6.99- 28.6.99	112.0	104.0	-7.1
28.6.99- 12.7.99	13.2	4.3	-67.3
12.7.99-25.7.99	113.3	97.0	-14.4
25.7.99-16.8.99	42.9	35.5	-17.3
16.8.99-2.9.99	49.3	43.2	-12.4
2.9.99-20.9.99	112.8	108.7	-3.6
20.9.99-10.10.99	161.8	148.6	-8.2
10.10.99-27.10.99	44.5	37.3	-16.0
27.10.99-9.11.99	186.2	182.9	-1.8
9.11.99-4.12.99	215.4	207.3	-3.8

4.4.4 Hillslope process activity during the measurement intervals

In the analysis of particle size data which follows the 7th January 1999 (start of measurement interval 5) will be used as the starting date. Because of complications in the period 13th November 1998 to 7th January 1999 (measurement intervals 1-4) these data will not be used. It should also be noted that the sampling design imposes artificial boundaries on the time series, for example measurements in the middle of February, and the 17th April split significant freeze-thaw periods.

7th January- 11th /14th February 1999 (Freeze-thaw): During this interval there were some significant rain events in January, achieving peak intensities of 6.6 mm h^{-1} (Table 4.2). Snowfalls were observed, and others are inferred on the basis of the temperature records, though in the absence of direct observation the nature of snowmelt is unknown. Throughout January, and more especially February 1999, freeze-thaw events were numerous (14 cycles occurred at the rock face, with a mean rock face temperature of 0.54 °C). Freeze-thaw activity was dominant between the 11th and 14th February, which caused an increase in sediment production. Field observations confirm the impact of rainfall, including a small localised debris flow intercepted by Gerlach troughs 2 and 3.

11th /14th February- 10th March 1999 (Freeze-thaw): Freeze-thaw activity was again significant, with 8 cycles from the 14th February 1999. This is reflected in the mean rock face temperature which is 0.87 °C. Field observations confirm enhanced sediment production with ravel deposits and angular rock fragments being deposited in all sediment traps. Also during this interval rainfall and snowfall occurred. Associated with the rainfall were wash deposits and rilling, though these are less significant than the effect of the freeze-thaw. Snowmelt slumps and balling occurred especially at the head of the secondary hillslope zone.

10th March- 23rd March 1999 (Rainfall): This interval had little freeze-thaw activity, with only 3 cycles and a higher mean temperature of 3.33 °C. However field observations indicate that material of a freeze-thaw origin caused choking of some rills and channels. Rainfall activity dominated and was typical of the winter phase of the sediment budget, i.e. average daily precipitation of about 6 mm and maximum intensity between 4 and 5 mm h^{-1} (Table 4.2). However, the mean rain event (duration of 8.6 hours and mean depth of 11.2 mm) is one of the largest in the sediment budget monitoring period. The direct effect of the rainfall is expressed in the enlargement of the rill network.

23rd March- 17th April 1999 (Freeze-thaw): This early spring interval was influenced by a return to winter conditions. The increasing mean temperature of 4.65 °C disguises the 9 freeze-thaw cycles and two snowfall events that occurred. The second snowfall on the 12-13th April 1999 was one of the most significant observed during the sediment budget, with windblown accumulations in the primary hillslope zone between 1 and 2 metres deep (17th April 1999). As in February/ March 1999 slumping and balling of snow occurred, but the effects were localised. The evidence of freeze-thaw activity was very marked, with needle ice growth and fresh deposition of angular rock and ravel. With the exception of one rain event that lasted 21 hours (yielding 42 mm of rain), most events were small and of low intensity, which is reflected in the values in Table 4.2.

17th April- 29th April 1999 (No dominant process type): On the afternoon of the 17th April 1999, following the emptying of instruments the melting and collapse of heaved ground was observed to release large amounts of sediment. This activity was mainly limited to the secondary hillslope zone where a discontinuous cover of snow existed. Material was deposited in many of the instruments. Following this 5 further freeze-thaw cycles occurred. The interval also included a prolonged spell of rainfall (20th to 22nd April 1999), and the formation of a crust and associated dry ravel resulting from warm/ dry conditions. As a result of this range of processes the sediment signatures in the instruments are expected to be a composite with no single process being dominant.

29th April- 17th May 1999 (No dominant process type): The crust observed in late April 1999 was still present. A variety of surface processes operated including: trampling by sheep (especially lambs), dry ravel flows, and sheetwash due to rainfall. Table 4.2 shows the rainfall events were of short to moderate duration (mean 5.5 hours) and of moderate intensity (not exceeding 4.6 mm h^{-1}). The sediment collected in this interval was the result of composite process activity, namely: crust fragmentation, sheetwash, and dry ravel.

17th May- 31st May 1999 (No dominant process type): A virtual repeat of the previous interval occurs. The crust continues to fragment under the influence of sheep trampling. Rainfall of shorter mean duration (4.6 hours), and greater maximum (5.3 mm) and mean intensity (1.6 mm h^{-1}), leads to rilling as observed in the incision of the hillslope deposits and basal ravel cones.

31st May- 12th June 1999 (Dry ravel and wind): During this interval rainfall was of less significance. The maximum duration was seven hours, maximum event depth of 8.6 mm, and a mean intensity of 0.9 mm h^{-1}. Sheep trampling continued, but the heaved crust had largely disappeared. Dry ravel flows were seen, particularly in the secondary hillslope zone. Wind also transported finer sediment, and disturbed ravel, that was then transported under the influence of gravity. This measurement interval is characterised by a combination of dry ravel flows and to a lesser extent wind transport.

12th June- 28th June 1999 (Rainfall events, storm of 19.6.99): Rainfall events dominated with a major rainfall event on the 19th-20th June 1999. This lasted over 17 hours and produced over 48 mm of rainfall, with a peak intensity of 7.9 mm h^{-1} (Table 4.2). The mean duration of rainfall events in this interval was 5.3 hours. This was not higher than the long-term mean. However, the mean depth of 9.7 mm is amongst the highest values, and the mean intensity of 1.9 mm h^{-1} is the highest value on record. Other rainfall events were also of similar magnitude. Field observations on the 26th June 1999 indicate the presence of extensive rilling and sheetwash. The Gerlach troughs in the secondary hillslope zone collected relatively little sediment, suggesting concentrated flows missed the instruments. The rills were freshly incised in the hillslope sediment, although existing rills also transported sediment. Further observation on the 28th June 1999 indicated little change in the site morphology following the storm of the 19th June 1999, despite several intervening rainfall events. Therefore the sediment collected by the instruments is largely the result of rill and sheetwash processes generated by the rain storm of the 19th June 1999.

28th June- 12th July 1999 (Dry ravel): Dryness and warm temperatures characterised the first 2 weeks of July 1999. Rainfall was minimal with only 13.2 mm falling in 14 days (daily average precipitation value of 0.9 mm). When rain did occur, it was short duration (maximum 5 hours), low depth (maximum 2.5 mm) and low intensity (maximum 1 mm h^{-1}). The mean temperature of 14.54 °C is the highest throughout the monitoring period. Field observations confirm this dryness, as the absence of water allowed sediment cones at the base of slopes to develop. These cones and slope deposits were produced by dry ravel flows, sometimes initiated by sheep trampling.

12th July- 25th July 1999 (Rainfall): This interval was dominated by rainfall, with a mean daily rainfall of 8.7 mm. This is not as great as the mean daily values that generally result when a large storm occurs (Table 4.2). Rainfall duration and intensity are not particularly high. Field observations suggest no significant activity on the hillslopes.

25th July- 16th August 1999 (No dominant process type): On the whole this was a hot/ dry interval; temperatures peaked just below 32 °C, with a mean of 13.46 °C. Rainfall was 42.9 mm in 22 days (daily average of 2 mm). The mean duration was 4 hours, the maximum depth small at 6.4 mm, and the maximum intensity a relatively low 3.8 mm h^{-1}. Field evidence suggests some sheetflow and rilling, though this was weak.

16th August- 3rd September 1999 (Dry Ravel): This similar to the previous measurement interval, characterised by warm/ dry conditions (maximum temperature is 21.33 °C, mean 10.83 °C), interrupted by rainfall of limited significance. Dry ravel flows are inferred from the growth of basal slope cones, and an increase in sheep trampling frequency.

3rd September- 20th September 1999 (Rainfall): This interval is again warm, with a maximum temperature of 24 °C and a mean of 11.29 °C, but is considerably wetter than late August 1999. The rain events were characteristically of short duration (maximum 9 hours, mean 4.6 hours), and higher intensity (maximum 8.1 mm h^{-1}, mean 1.6 mm h^{-1}). Associated slope activity included evidence of rainsplash and rilling, though features were not widespread.

20th September- 10th October 1999 (Rainfall): This was another wet interval, having an average rainfall of 8.1 mm rain per day (162 mm over 20 days). The maximum duration was 17 hours. Mean depth was 6.5 mm. The intensity peaked at 6.4 mm h^{-1}, though most hourly values are lower. Fresh rills were observed, but slope activity was generally low.

10th October- 27th October 1999 (Rainfall): This was a quiet interval, with declining mean temperatures and little rainfall. Daily rainfall averaged 2.6 mm; was of short duration (maximum 8 hours); and had a low mean intensity (0.9 mm h^{-1}). Rilling of the hillslope sediment was noted but on the whole this measurement interval was eventless.

27th October- 9th November 1999 (Rainfall- specifically storm of 4-5th November 1999): This was a very wet time, having 186.2 mm of rain over 13 days (mean of 14.3 mm d^{-1}). Similar to the second half of June 1999, this interval was dominated by a single rainstorm, on the 4th and 5th November 1999. Eden (1999) states Seathwaite, Cumbria, was the wettest place in Europe for the first week of November, recording 176.5 mm over the two-day period. At Iron Crag during this 48 hours 86.9 mm of rain fell, which was 46.7 % of the total rainfall occurring in the measurement interval. The overall event was considered to be 3 separate events. The main event lasted 28 hours and accounted for 63 mm of the total falling over the 2 days. The maximum intensity of rainfall during the storm was 7.6 mm h^{-1}, though this was exceeded during the measurement interval by another significant rain event on the 1st November 1999, when 8.6 mm h^{-1} was recorded. Correspondingly the mean intensity value for the measurement interval is high at 1.6 mm h^{-1}. These storms of the first week of November 1999, which caused significant flooding of the western Cumbrian towns of Whitehaven, Egremont, and Cleator Moor (Story *et al.*, 1999; Lewis and Verinder, 1999), also caused a significant geomorphological impact at Iron Crag.

9th November- 4th December 1999 (Freeze-thaw and rainfall, specifically storm of 27-28th November 1999): This final interval was initially dry, with freeze-thaw cycles, followed by a wet spell. In the 25 days, 215.3 mm of rain fell, which corresponds to a mean daily fall of 8.6 mm. Again a single storm stands out from the rainfall series (27th - 28th November 1999). In this event 81.3 mm of rain fell over a 30 hour period. This storm also produced flooding in Cumbrian towns (Lake District Herald, 4.12.99; Connor, 1999). During the storm a maximum intensity of 9.7 mm h^{-1} was recorded, and the mean intensity for the measurement interval was high at 1.7 mm h^{-1}. Snowfall also occurred at the end of the interval, though this had not melted when the instruments were emptied. The sediment supplied to the instruments was a combination of freeze-thaw activity and subsequent wash by rainfall, however observations of rill development were limited.

This section has outlined the processes responsible for the deposition of sediment in the Gerlach troughs and nets at Iron Crag, between 7th January 1999 and 4th December 1999. From a synthesis of meteorological data, and field observations it has been suggested that either: (a) single processes can dominate sediment delivery in a particular measurement interval, or (b) a multitude of processes are responsible.

4.4.5 Particle size data of sediments collected during the sediment budget monitoring period

Following Section 4.3.3, graphical statistics are derived from the calculated particle size distributions. Two Fortran 77 programs run in MS-DOS (SIZEDATA [version: 1.10 1995/ 06/ 02] and SEDSIZE [version 1.9 1997/ 06/ 02]) are used to calculate percentile values of a particle size distribution in phi units, and the associated graphical statistics. The program calculates graphical statistics according to the equations of Trask (1932); Inman (1952); and Folk (1968, 1974). In this analysis the equations of Folk are used (equations 4.1; 4.2; and 4.3), and therefore all considerations of particle size are made in Phi units. For a discussion of these graphical approaches see Folk (1974). These freeware packages are available on the Internet, as part of the United States Geological Survey (USGS)- Water Resources Applications Software World Wide Web pages. Documentation providing the program code and explanation of its operation are found on the USGS web pages and in Stevens and Hubbell (1986).

The analysis of the graphical statistics for each instrument during measurement intervals are as complete as possible. Statistics are not calculated for nets which were subject to channel sediment deposition, and those Gerlach troughs which performed poorly. The analysis is performed at two scales, first a general analysis of the data as a precursor to the more specific event-based analysis of process activity.

4.4.5.1 General analysis of graphical statistics

All data

Figures 4.2, 4.3, and 4.4, illustrate the relationships between mean size and sorting; mean size and skewness; and sorting and skewness, respectively. In these plots all the available data are used with no segregation (n = 439). Figure 4.2 shows coarser particle size distributions (higher negative phi value) are better sorted. An R^2 value of 0.4754 is calculated for this relationship, and the correlation is significant at the 5% level with a calculated p-value of less than 0.00001. Figure 4.3 shows a weaker relationship between mean and skewness (R^2 is 0.3132), though indicates that the finer the sediment (lower negative phi value) the less skewed the particle size distributions. This relationship is again significant with a p-value less than 0.00001. Figure 4.4 shows that with higher values of sorting, skewness declines, but this relationship is weak with a R^2 of 0.1212. Nevertheless it is still a significant negative relationship with a p-value once more less than 0.00001. Collectively these relationships indicate that better sorted sediments are composed of a greater proportion of coarse particles, which in turn is reflected in a positively skewed distribution (i.e. fine tail).

All data with effect of instrument type shown

Figures 4.5, 4.6, and 4.7, like the previous bi-variate plots use the complete data series, though they distinguish between the instrument type- Gerlach troughs or nets. In all the Figures the direction of the relationships are identical to those previously identified, but the strength and significance of the relationship as measured by R^2 and p values differ. The objective here is to assess which bi-variate relationship best distinguishes the differences between sediment collected by Gerlach troughs and nets.

Figure 4.5 shows the clustering of net and Gerlach trough sediments at opposite ends of the plot. In support of this a t-test of mean values according to instrument type, shows a significant difference between Gerlach troughs and nets to exist at the 5% level, with a calculated value 't' of 16.277 and a lower two-tailed critical value of

Figure 4.2: **Bivariate plot of mean particle size and standard deviation (sorting) -all data**

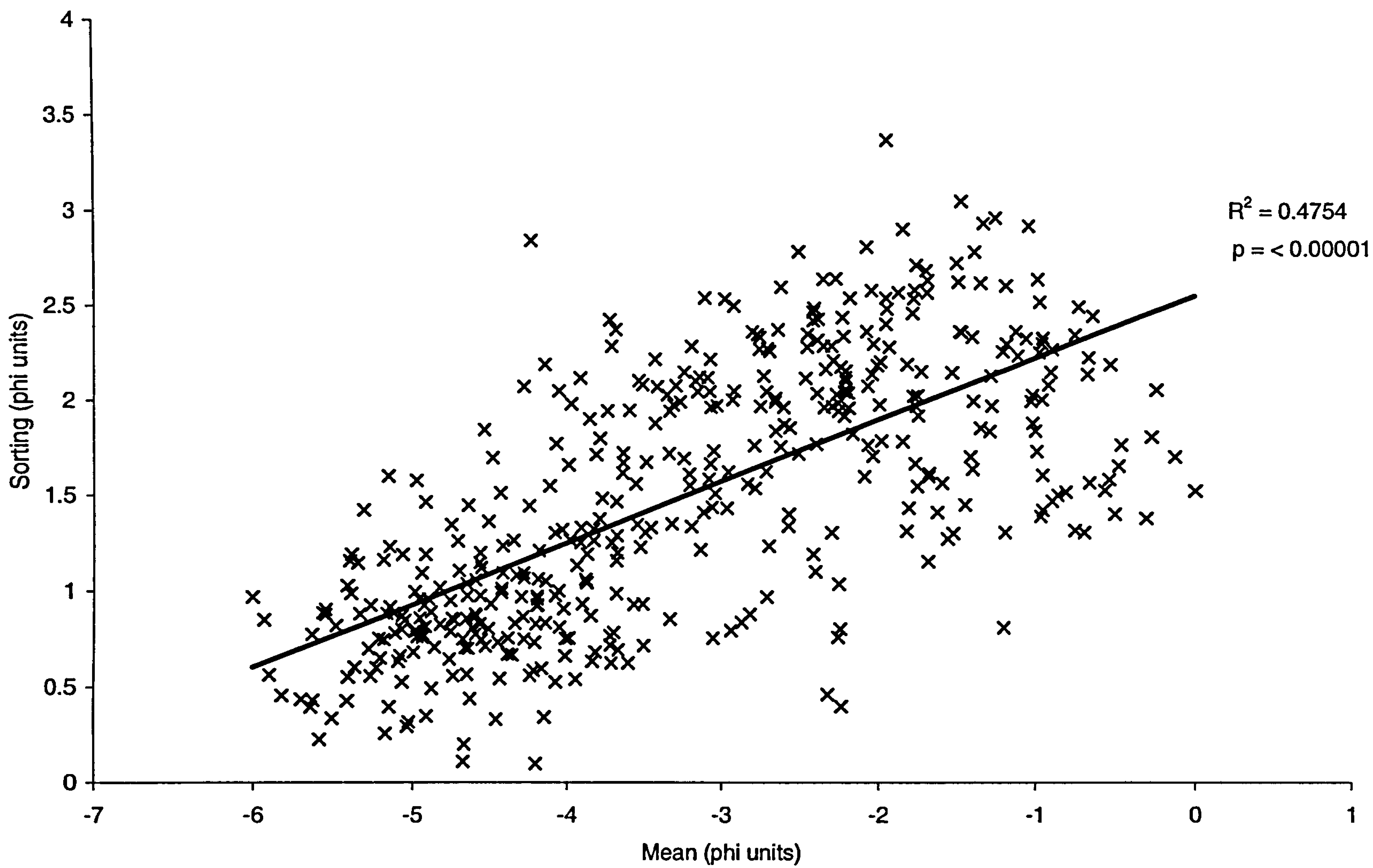


Figure 4.3: Bivariate plot of mean particle size and skewness- all data

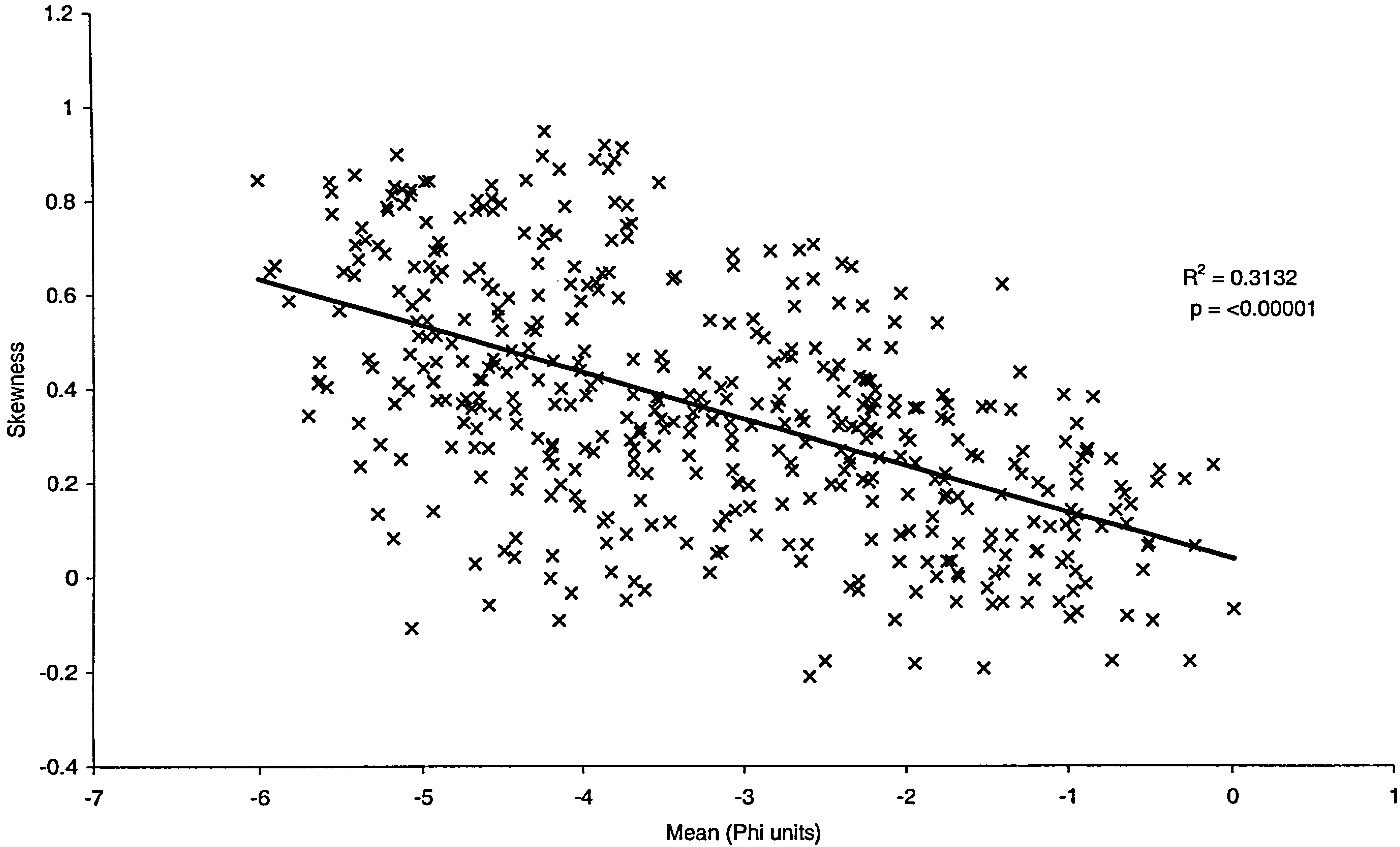
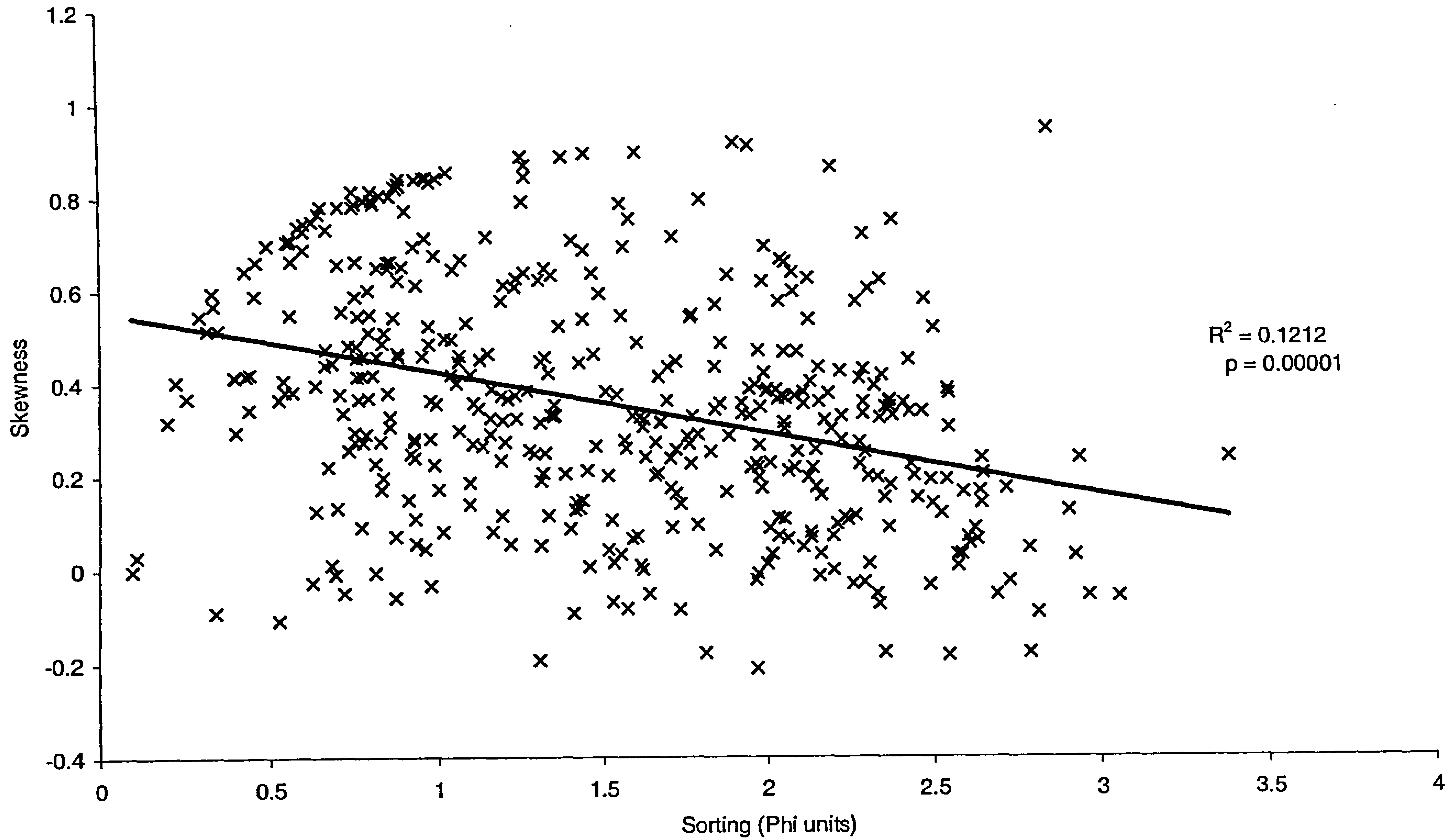


Figure 4.4: Bivariate plot of particle size sorting and skewness- all data



1.965. Similarly a significant difference in the comparison of sorting values is obtained, with a calculated t of 16.118. Hence the statistical test confirms the visual interpretation that net sediments tend to be coarser and better sorted, whilst Gerlach trough sediments are finer and more poorly sorted. Despite having established the statistical differences between instrument types, it is evident that some overlap still occurs. This is more the case with the net sediments that intrude more into the Gerlach trough cluster, than is the case the other way around. This can be explained by the different abilities of each instrument type to collect sediment. This observation supports the field observations reported in section 4.4.2, which state nets have an ability to collect finer sediment in addition to rockfall; and Gerlach troughs have an upper size limit dictated by the aperture of the trough. With regard to the strength and significance of the regressions between mean particle size and sorting, the R^2 values and p-values indicate that net sediments have a better correlation than Gerlach troughs: nets values are 0.4362 (R^2), and a significant p-value of less than 0.00001 at the 5% level; Gerlach troughs are 0.1058 (R^2) and a significant p-value of less than 0.0001 at the 5% level.

Figures 4.6 and 4.7 also show net and Gerlach trough data pairs to dominate different ends of the plot. The calculated t statistic of –5.415 for skewness is greater than the critical value at the 5% level (1.965), therefore the null hypothesis is rejected. Hence a statistically significant difference exists between Gerlach troughs and nets with regard to this graphical statistic. With regard to the regressions for Figures 4.6 and 4.7, the general observation is that the instrument division reduces the R^2 values, relative to those calculated for Figures 4.3 and 4.4, with the exception of one R^2 value in Figure 4.6 which is slightly increased. R^2 values in Figure 4.6 are 0.3545 ($p < 0.00001$ at 5% level) for Gerlach troughs and 0.2355 ($p < 0.00001$ at 5% level) for nets. Correspondingly in Figure 4.7 values are 0.0506 ($p < 0.0018$ at 5% level) and 0.0806 ($p < 0.0001$ at 5% level).

Figure 4.5: Bivariate plot of mean particle size and sorting, with the type of instrument indicated

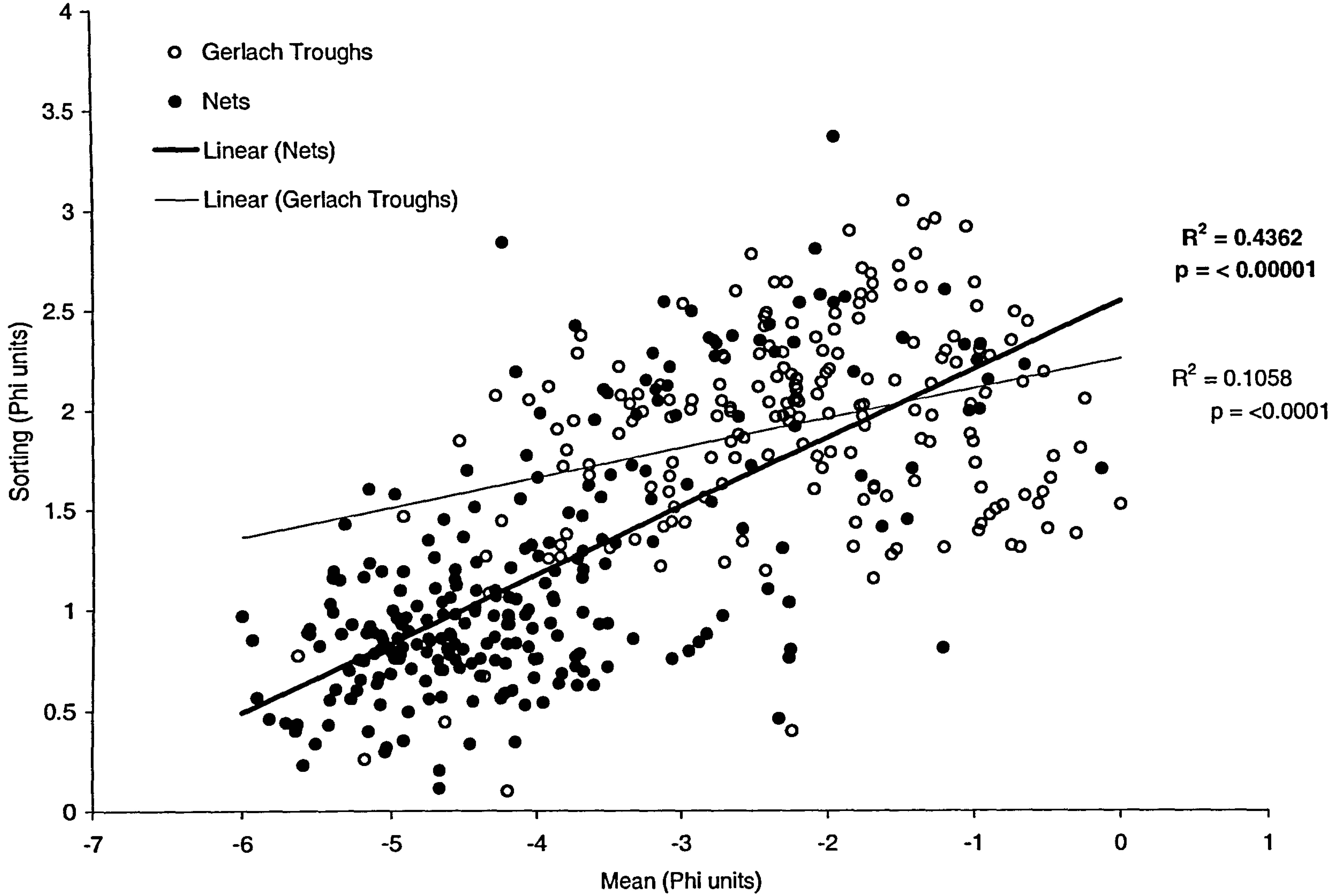


Figure 4.6: Bivariate plot of mean particle size and skewness, with type of instrument indicated

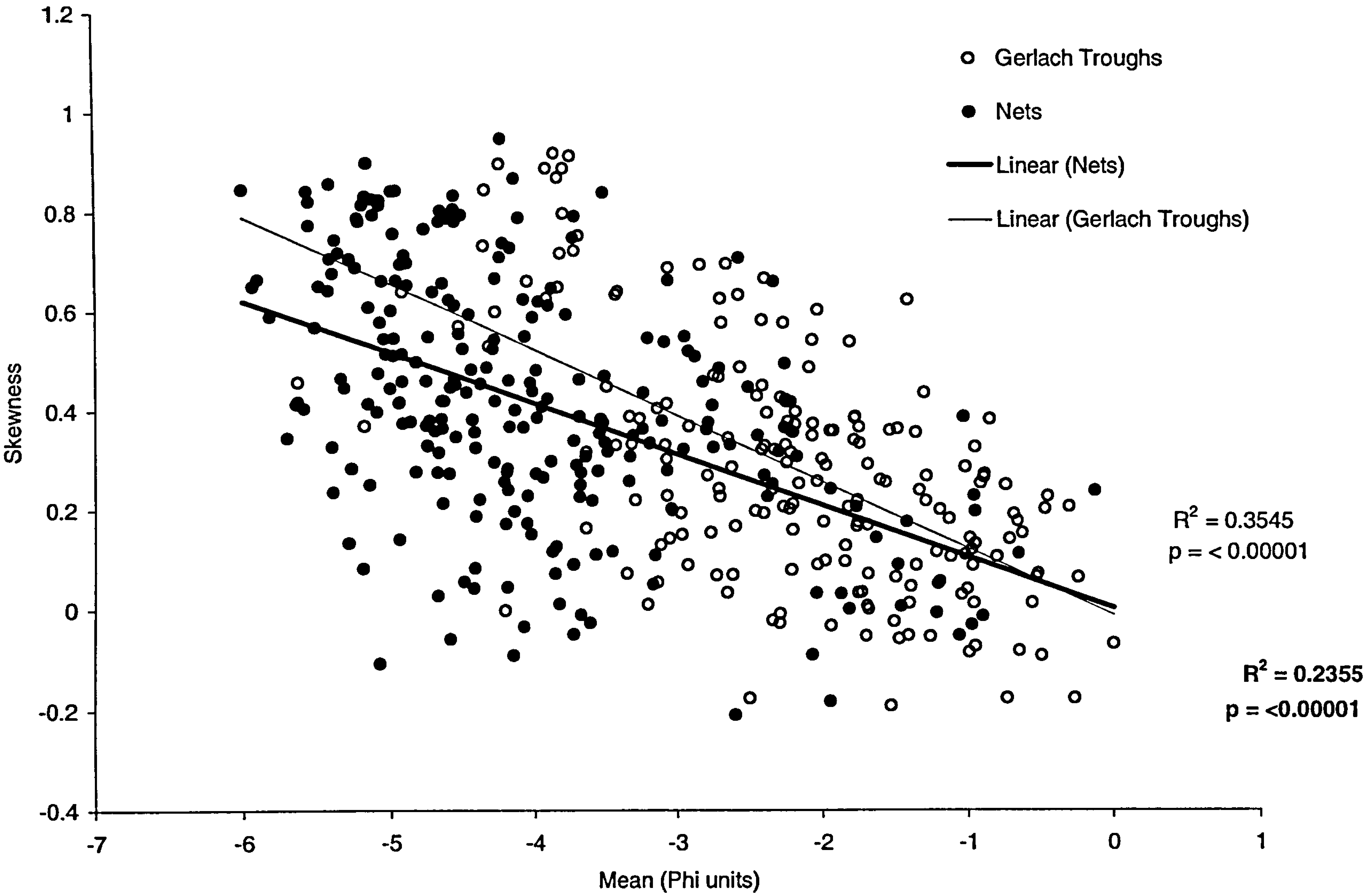
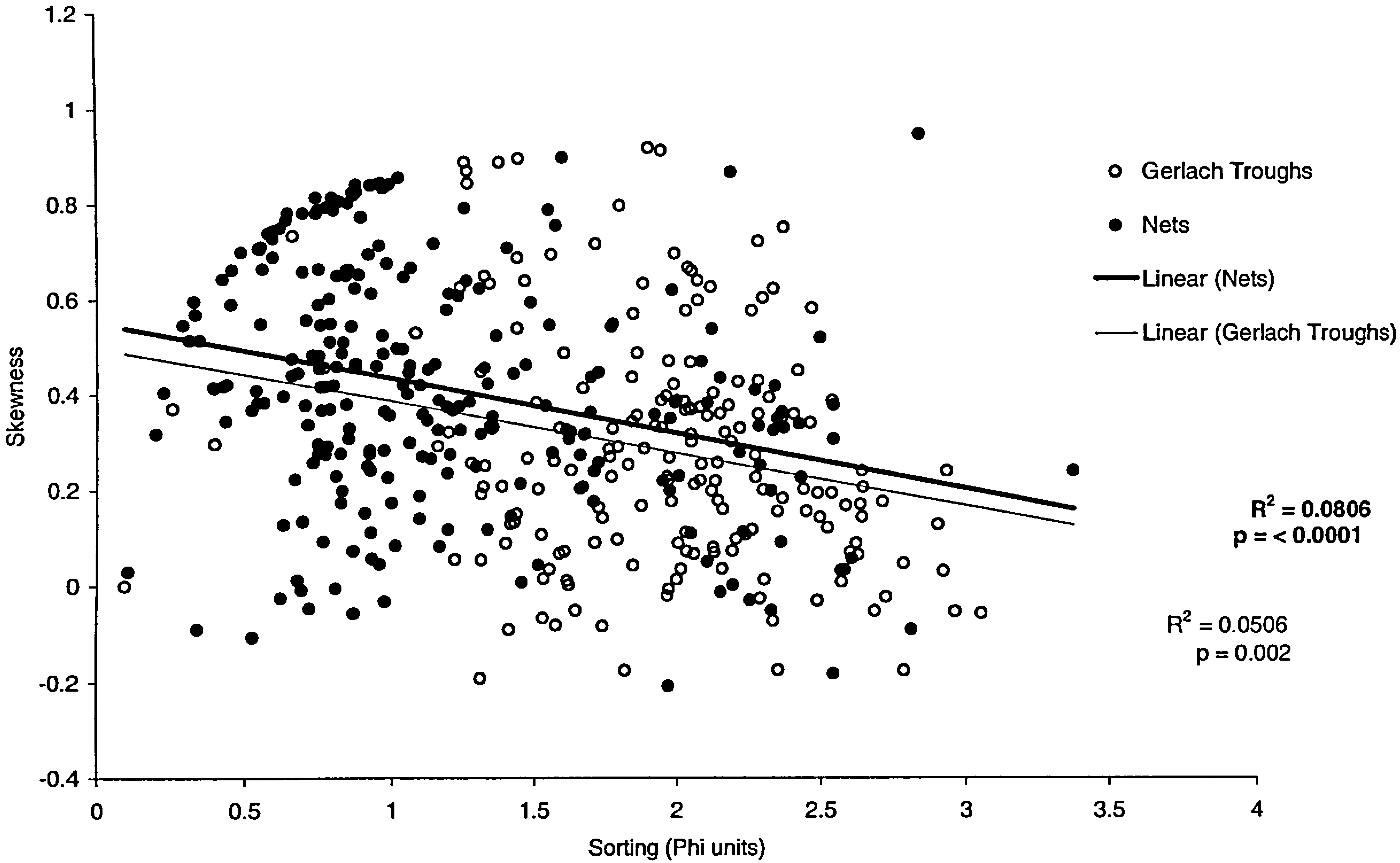


Figure 4.7: Bivariate plot of particle size sorting and skewness, with the type of instrument indicated



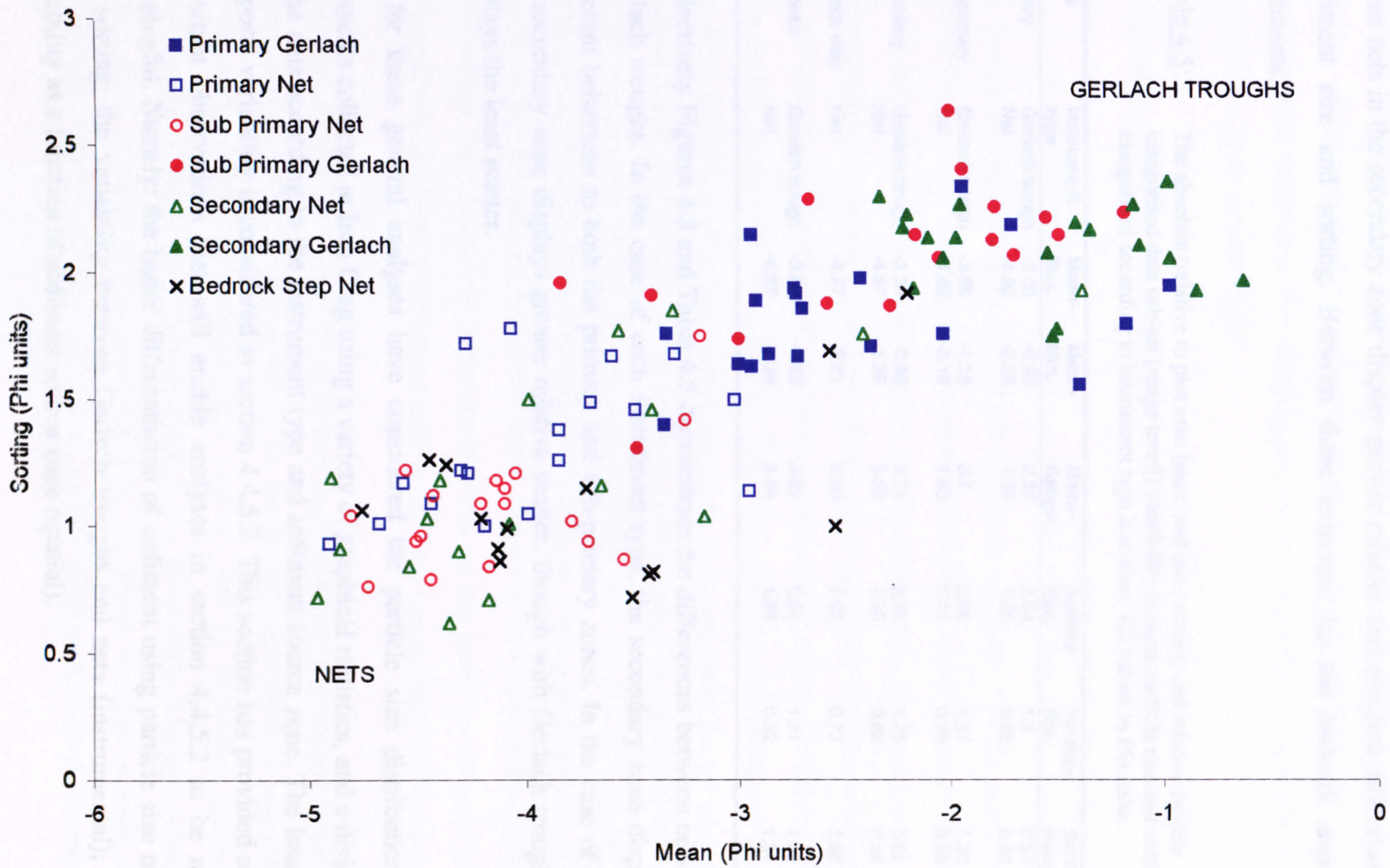
Figures 4.5, 4.6 and 4.7 collectively illustrate that nets and troughs collect different grades of sediment and the hypothesis of overlap in sediment collection is not statistically confirmed. However the visual observation of overlap is sufficient that caution should be applied in the subsequent analysis of process type, especially with regard to net sediments which exhibit greater scatter in sediment characteristics. In reference to the overall objective it is shown that all variables show statistically significant differences between sediments from each instrument type. However, the mean and sorting show the greatest separation, therefore in this context the further use of these two variables is justified.

Particle size characteristics: mean data, instrument type and spatial differentiation

To provide further insight into the data Figure 4.8 shows a modified view of the relationship between mean particle size and sorting. Not all data points are shown, instead average values are calculated for each measurement interval, according to instrument type and the sediment source zone. Thus a single data point is the average of all mean particle size and sorting values, for either Gerlach troughs or nets in each sediment source zone, in each measurement interval. The number of points plotted is a reflection of the data available.

Similar to Figure 4.5, the different plotting positions between Gerlach troughs and nets data are clearly shown (Figure 4.8). This is expected because the averaging procedure removes extreme values and produces clearer separation between values. Figure 4.8 and Table 4.5 demonstrate that in the case of primary and sub-primary zones relative variability in sorting and mean sediment size is greater for Gerlach troughs than nets. Better relative sorting (less range) of the nets supplements the previous finding that nets contain sediment which is better sorted. Though in the secondary zone this behaviour is reversed, i.e. nets display a broader range of relative sorting than do Gerlach troughs. It could be suggested that this is a reflection of a few anomalous sediment samples. However, it may truly reflect the material properties received by nets during the monitoring interval, especially the collection of finer worse sorted sediments as suggested in section 4.4.2.1.

Figure 4.8: Bivariate plot of mean particle size and sorting according to zone and instrument type



Nets in the sub-primary are clustered (sorting range 0.99 ϕ), but not as much as the primary zone (sorting range 0.85 ϕ). Correspondingly, the relative mean size is greater in the primary than the sub-primary zone. Despite the similar relative variations, on the absolute scale, nets in the primary zone tend to collect coarser and worse sorted sediment than those in the sub-primary zone. In contrast to both these zones nets in the secondary zone display greater relative and absolute differences in sediment size and sorting. Between these extremes lie the bedrock step net sediments.

Table 4.5: The absolute (relative to plot axes [max. and min. terms]) and relative (within categorised data sub-set [range term]) variability in mean particle size and sorting, categorised according to instrument type and zone. All values in Phi units.

Zone	Instrument type	Mean-Max.	Mean-Min.	Mean-Range	Sorting-Max.	Sorting-Min.	Sorting-Range
Primary	Gerlach trough	-3.36	-0.98	2.38	2.34	1.4	0.94
	Net	-4.92	-2.96	1.96	1.78	0.93	0.85
Sub-primary	Gerlach trough	-3.85	-1.15	2.7	2.64	1.31	1.33
	Net	-4.82	-3.19	1.63	1.75	0.76	0.99
Secondary	Gerlach trough	-2.34	-0.63	1.71	2.36	1.75	0.61
	Net	-4.97	-1.39	3.58	1.93	0.62	2.55
Bedrock step	Net	-4.77	-2.21	2.56	1.92	0.72	1.20
All zones	Gerlach trough	-3.85	-0.63	3.22	2.64	1.31	1.33
	Net	-4.97	-1.39	3.58	1.93	0.62	1.31

Collectively Figures 4.8 and Table 4.5 demonstrate the differences between nets and Gerlach troughs. In the case of each instrument type, the secondary zone displays different behaviour to both the primary and sub-primary zones. In the case of nets the secondary zone displays greater relative scatter, though with Gerlach troughs it displays the least scatter.

So far these general analyses have considered the particle size distribution of sediments collected at Iron Crag using a variety of graphical statistics, and a division of the data according to the instrument type and sediment source zone. The issue of temporal variability is considered in section 4.4.5.2. This section has provided some important observations that will enable analyses in section 4.4.5.2 to be more meaningful. Namely: the better differentiation of sediment using particle size mean and sorting; the variability between Gerlach troughs and nets (instrumental); and variability as a function of sediment source zone (spatial).

4.4.5.2 Event based analysis of graphical statistics

If the activity summarised in Section 4.4.4 is taken to be a reasonable account of the processes operating in a measurement interval, then the particle size distribution of sediments collected by instruments can be said to reflect the dominant process identified. Therefore it is possible to conduct a number of analyses on the graphical statistics which specifically consider process type. These include the temporal variability with reference to the changing process in the data series, and particle size signature of a given process type.

Gerlach troughs- monitoring sediments

Figures 4.9 and 4.10 indicate the temporal variation in the sorting and mean particle size. Values are the average of all Gerlach troughs in each zone in each measurement interval. Figure 4.9 shows that the sorting of sediments is broadly constant between 11.2.99 and 4.12.99. More subtle changes are also discernible. Until the end of June 1999 sediments in the primary and secondary zones generally become worse sorted The sub-primary is more variable, but also increases to a peak in mid July1999. All zones decline sharply thereafter into late July 1999. Between this point and the 20th September 1999 all zones show a fluctuating rise, most especially the primary zone. A second major decline occurs between mid (sub-primary) and late October 1999 (primary and secondary). The final trend is an increase to the 11th November 1999. When process types are considered it is observed that a given process can cause both an increase and decrease in the plotted values of a given zone data series. Further a given process type during one measurement interval can cause an increase in the plotted value in one zone, but a corresponding decrease in a value in another zone.

Figure 4.10 displays the temporal variation of mean sediment size trapped in Gerlach troughs. In common with Figure 4.9 it is seen that the size of sediment both increases and decreases in any one measurement interval, and an individual process at different points in time causes opposite changes in a given zone. Greater consistency is once more observed in the general trends. All zones transport coarser sized particles until middle/ late April 1999. Then a period of finer sediment dominates to

Figure 4.9: Temporal variability in sorting values of sediment collected by Gerlach troughs

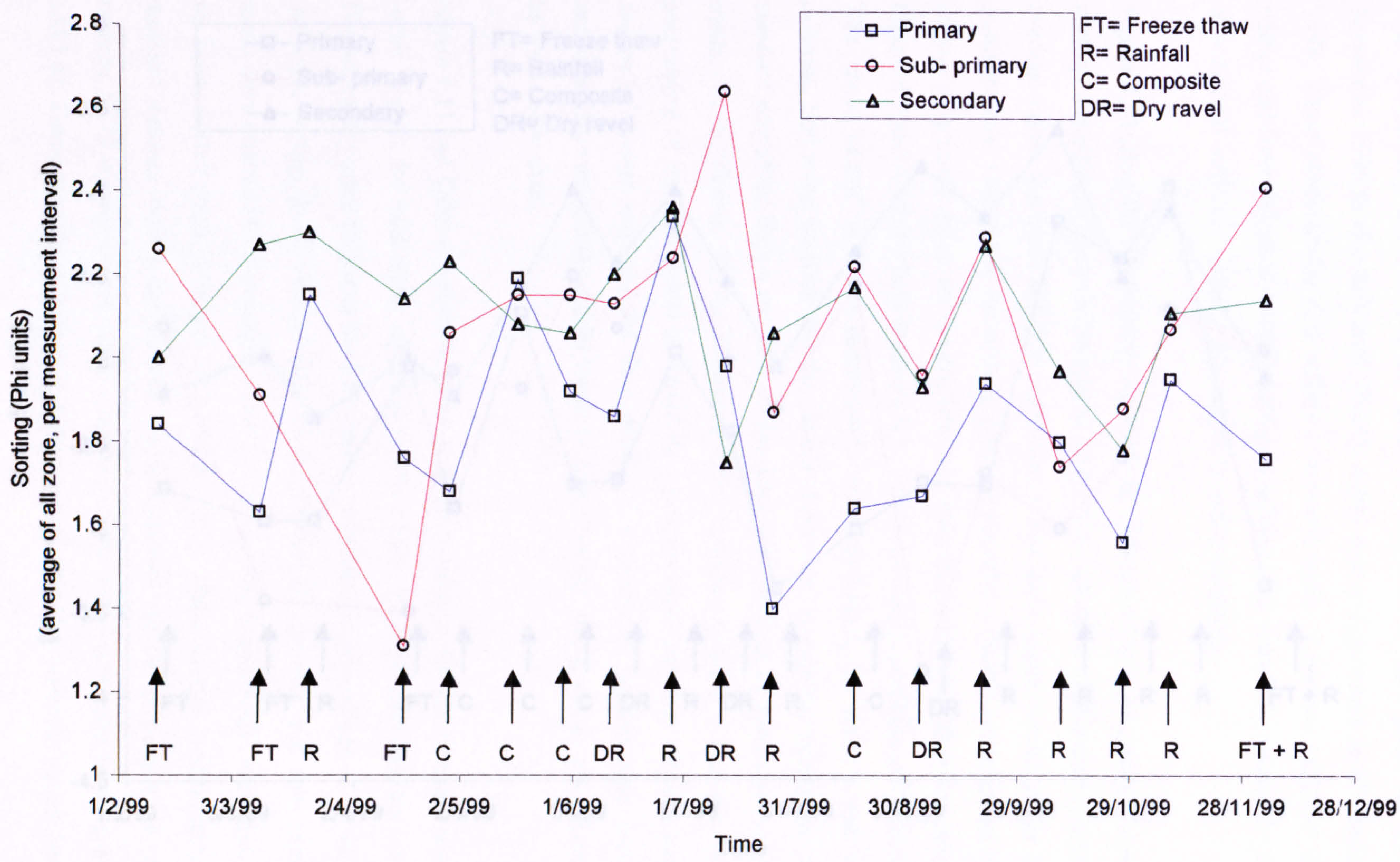
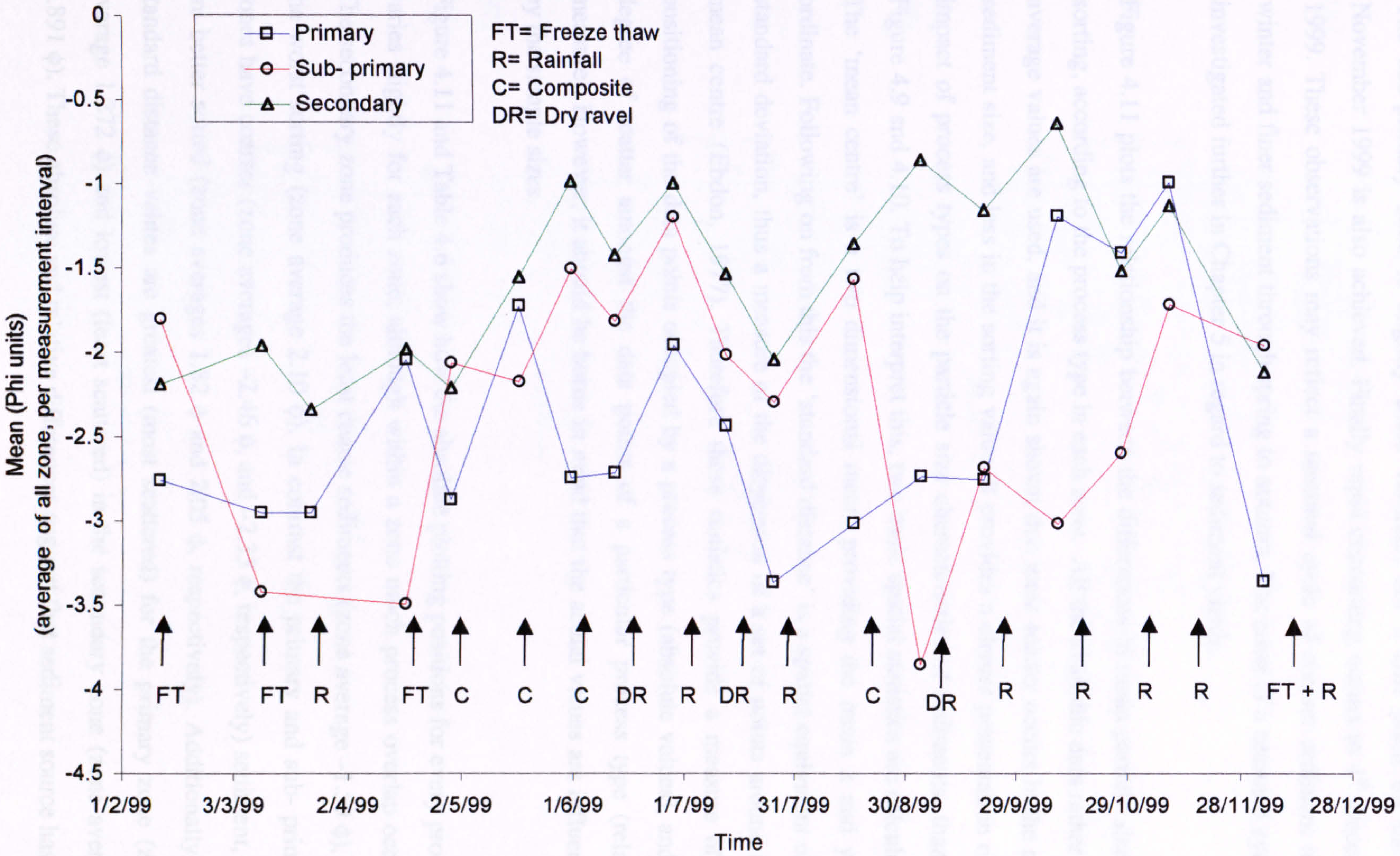


Figure 4.10: Temporal variability in mean values of sediment collected by Gerlach troughs



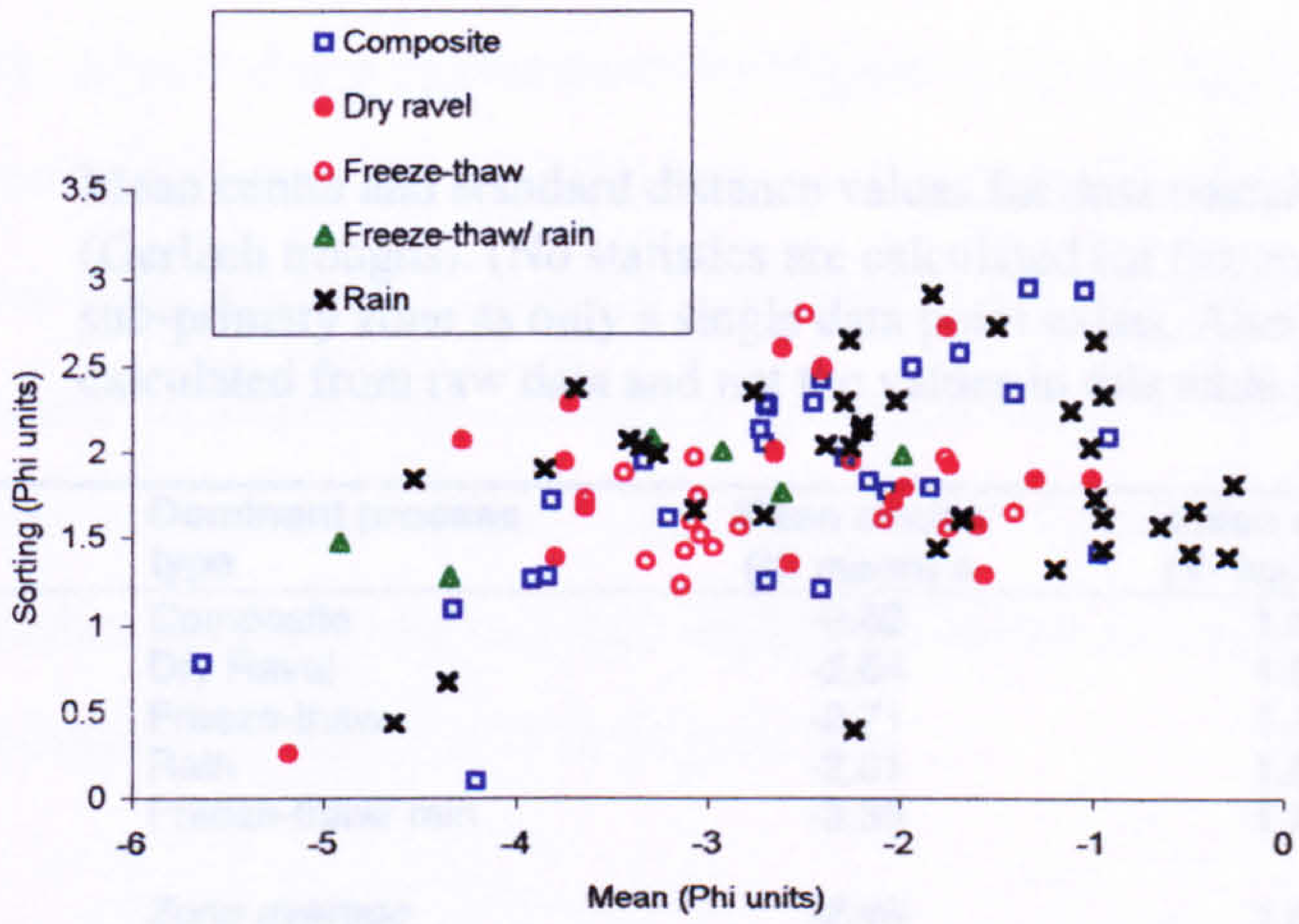
the end of June 1999. A short period of sediment coarsening prevails until the 25th July 1999, which is followed by a substantial reduction in particle size that is maintained until the middle of November 1999 in the primary and secondary zones. The sub-primary zone is slightly more variable, but a fine point on the 11th November 1999 is also achieved. Finally rapid coarsening occurs to 4th December 1999. These observations may reflect a seasonal cycle of coarser sediment in the winter and finer sediment through spring to autumn. The issue of a seasonal cycle is investigated further in Chapter 5 in regard to sediment yields.

Figure 4.11 plots the relationship between the differences in mean particle size and sorting, according to the process type in each zone. All the available data rather than average values are used, and it is again shown that most scatter occurs in the mean sediment size, and less in the sorting value. It provides a clearer presentation of the impact of process types on the particle size characteristics of sediments, than did Figure 4.9 and 4.10. To help interpret this, two basic spatial statistics are calculated. The 'mean centre' is a two dimensional mean, providing the mean x and y co-ordinate. Following on from this the 'standard distance' is a spatial equivalent of the standard deviation, thus a measure of the dispersion of a set of points around their mean centre (Ebdon, 1977). Therefore these statistics provide a measure of the positioning of the data points occupied by a process type (absolute values), and the degree of scatter amongst the data points of a particular process type (relative measure). However, it should be borne in mind that the actual values are influenced by the sample sizes.

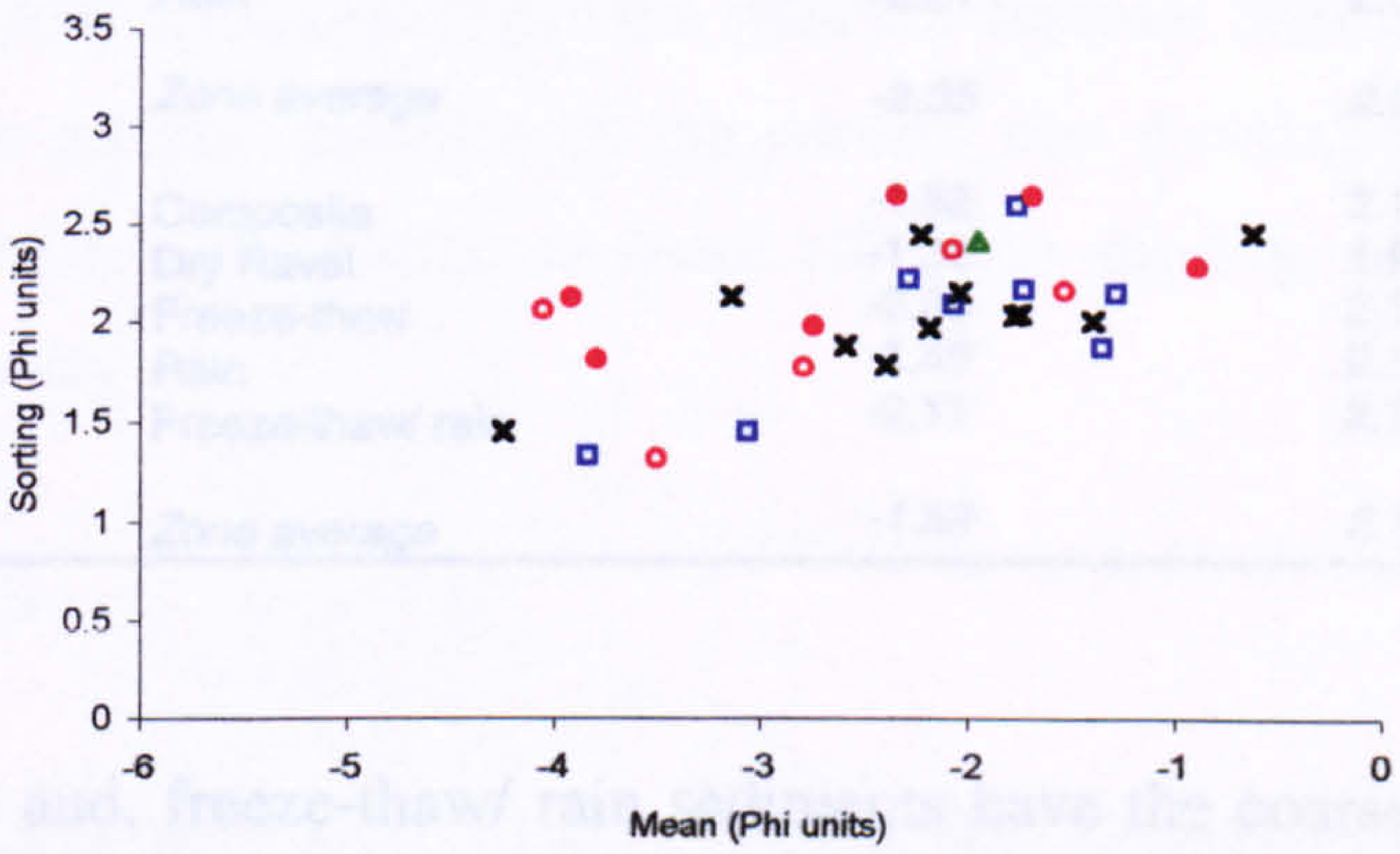
Figure 4.11 and Table 4.6 show how the absolute plotting positions for every process varies slightly for each zone, although within a zone much process overlap occurs. The secondary zone produces the least coarse sediments (zone average –1.59 ϕ), and the worst sorting (zone average 2.10 ϕ). In contrast the primary and sub- primary zones have coarser (zone averages –2.46 ϕ, and –2.35 ϕ, respectively) sediment, and are better sorted (zone averages 1.82 ϕ and 2.05 ϕ, respectively). Additionally the standard distance values are greatest (most scattered) for the primary zone (zone average 1.272 ϕ) and lowest (least scattered) in the secondary zone (zone average 0.891 ϕ). These absolute and relative differences suggest that sediment source has an

Figure 4.11: The variability in Gerlach trough sediments, categorised according to dominant process activity. (A) Primary zone, (B) Sub-primary zone, and (C) Secondary zone

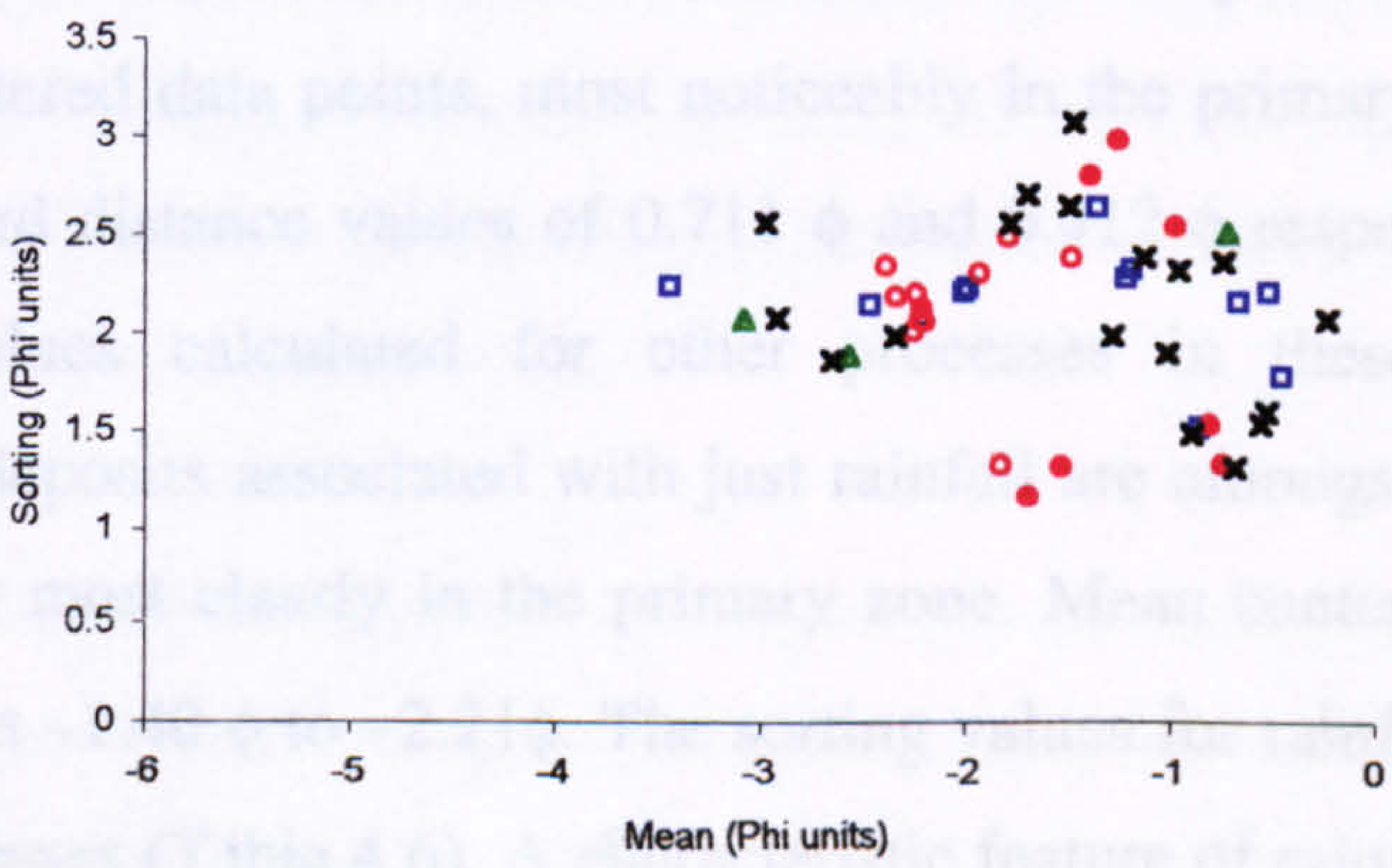
(A)



(B)



(C)



observable impact on processes entraining and transporting sediment. An implication of this finding is that a comparison of process particle size characteristics on a single diagram with no zonal segregation would be invalid, as the spatial statistics would be inadvertently affected, due to the varying initial material properties in different zones (inferred from the mean centre values).

Table 4.6: Mean centre and standard distance values for data contained within Figure 4.11 (Gerlach troughs). (No statistics are calculated for freeze-thaw and rainfall in the sub-primary zone as only a single data point exists. Also zone averages are calculated from raw data and not the values in this table.)

Zone	Dominant process type	Mean centre (X- mean) ϕ	Mean centre (Y- sorting) ϕ	Standard distance ϕ
Primary	Composite	-2.62	1.84	1.292
	Dry Ravel	-2.64	1.82	1.258
	Freeze-thaw	-2.71	1.76	0.711
	Rain	-2.01	1.84	1.356
	Freeze-thaw/ rain	-3.35	1.76	1.045
	Zone average	*-2.46*	*1.82*	*1.272*
Sub- primary	Composite	-2.17	1.98	0.910
	Dry Ravel	-2.56	2.24	1.125
	Freeze-thaw	-2.78	1.93	0.985
	Rain	-2.21	2.03	0.933
	Zone average	*-2.35*	*2.05*	*0.999*
Secondary	Composite	-1.52	2.13	0.907
	Dry Ravel	-1.32	1.96	0.820
	Freeze-thaw	-2.06	2.12	0.412
	Rain	-1.40	2.12	0.936
	Freeze-thaw/ rain	-2.11	2.14	1.047
	Zone average	*-1.59*	*2.10*	*0.891*

Freeze-thaw and, freeze-thaw/ rain sediments have the coarsest mean centre values of all process types (range –3.35 ϕ to –2.06 ϕ), and correspondingly are the most sorted deposits (range 1.76 ϕ to 2.14 ϕ). Freeze-thaw deposits alone are also amongst the least scattered data points, most noticeably in the primary and secondary zones where standard distance values of 0.711 ϕ and 0.412 ϕ respectively, are noticeably less than values calculated for other processes in these zones (Table 4.6). Conversely, deposits associated with just rainfall are amongst the finest deposits in all zones, but most clearly in the primary zone. Mean center values for mean size range between –1.40 ϕ to –2.21ϕ. The sorting values for rainfall are similar to those of other processes (Table 4.6). A characteristic feature of rainfall deposits are higher standard distance values, which are amongst the most scattered, most especially in the primary zone (1.356 ϕ).

As rainfall events are associated with high scatter in the standard distance values, the variability of rainfall events is further assessed. Relationships between maximum and mean rainfall intensities in rainfall dominated measurement intervals (Table 4.2) with mean and sorting values are shown in Figure 4.12. With increased rainfall intensity the tendency is for sediment collected by Gerlach troughs to be finer and worse sorted. Most of the regressions in Figure 4.12 are however insignificant at the 5 % level given the large amount of scatter in the relationships. It is only some of the sorting values which achieve statistically significant results, specifically the primary zone in relation to maximum intensity (p value 0.021); and the primary and sub-primary zones with mean intensity (p values 0.004 and 0.025 respectively). These results contradict the expectation that higher intensity rainfall will cause the removal of coarser sediment as illustrated in Figure 4.1.

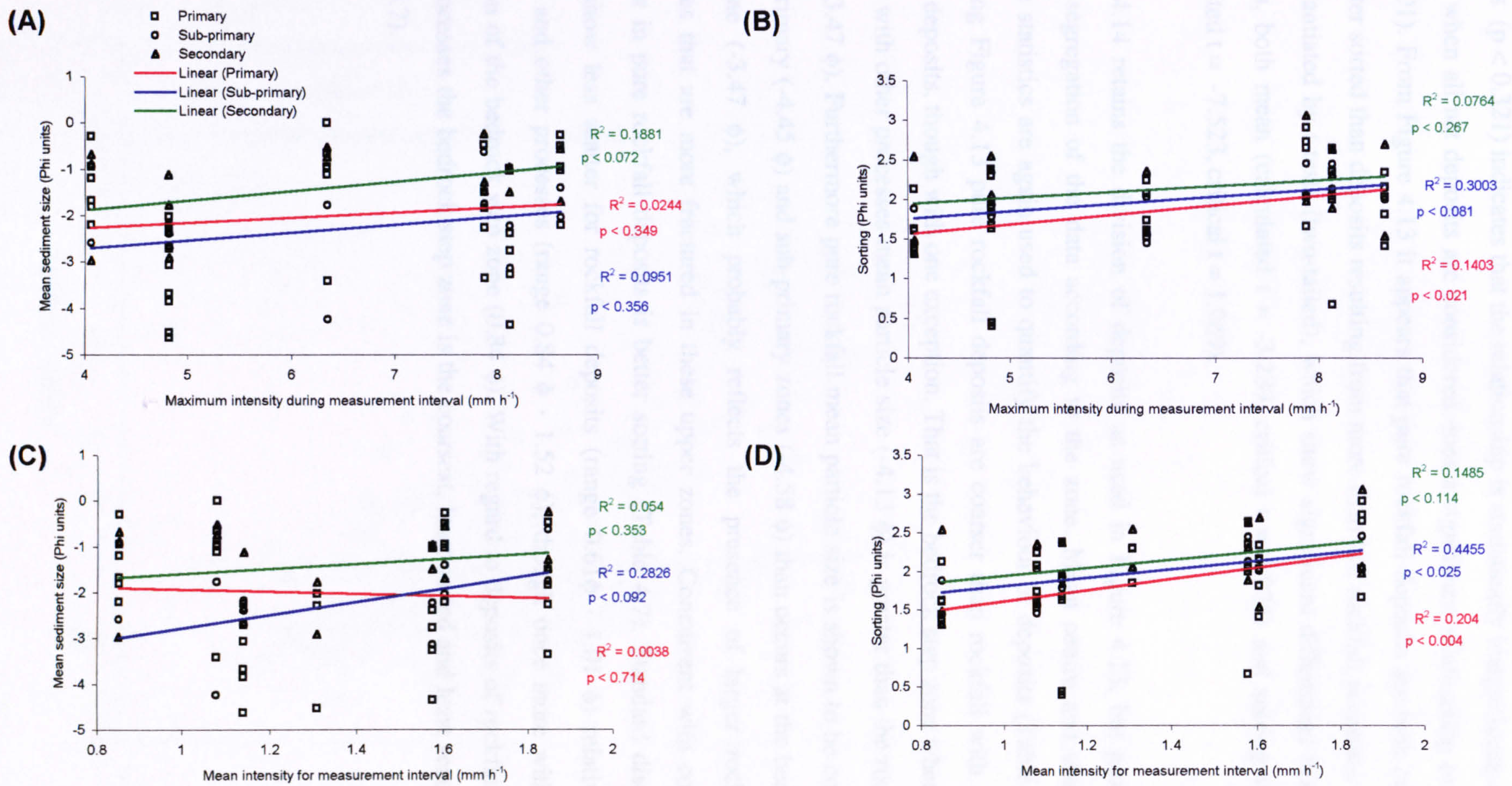
These analyses of Gerlach trough sediments according to process type and zone, indicate that subtle differences do exist between process type in both the mean centre values (absolute comparison) and the standard distance values (relative comparison). However the greater influence on the particle size distribution of sediment at Iron Crag is sediment source zone, as these affect the absolute positioning of data pairs for each process.

Net sediments

The data used in the analysis of net sediments are initially drawn from nets collecting both rockfall and sediment from other slope processes. However, more detailed analyses which consider the impact of process type only use nets collecting rockfall. This is because these pure rockfall sediments are the most representative of rockface breakdown. The result of this selection is a decline in the number of nets used to 5 out of the maximum number of 21.

Figure 4.13 outlines the relationships between mean particle size and sorting, with a division of the data according to the main supply process, i.e. rockfall only, and rockfall with other processes. The relationship between mean particle size and sorting is weakest for pure rockfall deposits ($R^2 = 0.0151$), though much stronger when other processes are involved ($R^2 = 0.5065$). The p-value for the pure rockfall

Figure 4.12: The relationship between rainfall intensity values with sediment mean size and sorting in the rainfall measurement intervals.
(A) Maximum intensity and mean size, (B) Maximum intensity and sorting
(C) Mean intensity and mean size, (D) Mean intensity and sorting



deposits ($p < 0.321$) indicates that the relationship is statistically insignificant, and it is only when all net deposits are considered does a significant relationship exist ($p < 0.00001$). From Figure 4.13 it appears that pure rockfall deposits are both coarser and better sorted than deposits resulting from more than just rockfall processes. This is substantiated by t-tests (two-tailed), which show significant differences between deposits, both mean (calculated $t = -3.289$, critical $t = 1.974$) and sorting values (calculated $t = -7.523$, critical $t = 1.969$).

Figure 4.14 retains the division of deposits as used in Figure 4.13, but provides further segregation of the data according to the zone. Mean centre and standard distance statistics are again used to quantify the behaviour of deposits (Table 4.7). Following Figure 4.13 pure rockfall deposits are coarser than rockfall with other process deposits, though with one exception. That is the bedrock step zone where the rockfall with other processes mean particle size (-4.13 ϕ) is greater than the rockfall value (-3.47 ϕ). Furthermore pure rockfall mean particle size is shown to be coarser in the primary (-4.45 ϕ) and sub-primary zones (-4.58 ϕ) than occurs at the bedrock step zone (-3.47 ϕ), which probably reflects the presence of larger rockface exposures that are more fractured in these upper zones. Concurrent with coarser sediment in pure rockfall deposits is better sorting (Table 4.7). Standard distance values show less scatter for rockfall deposits (range 0.61ϕ - 1.01 ϕ) relative to rockfall and other processes (range 0.84 ϕ - 1.52 ϕ), though once more with the exception of the bedrock step zone (0.84 ϕ). With regard to deposits of rockfall and other processes the bedrock step zone is the coarsest, least sorted and least scattered (Table 4.7).

Figure 4.13: Mean particle size and sorting distinguishing between nets collecting just rockfall and those collecting sediment from other processes as well.

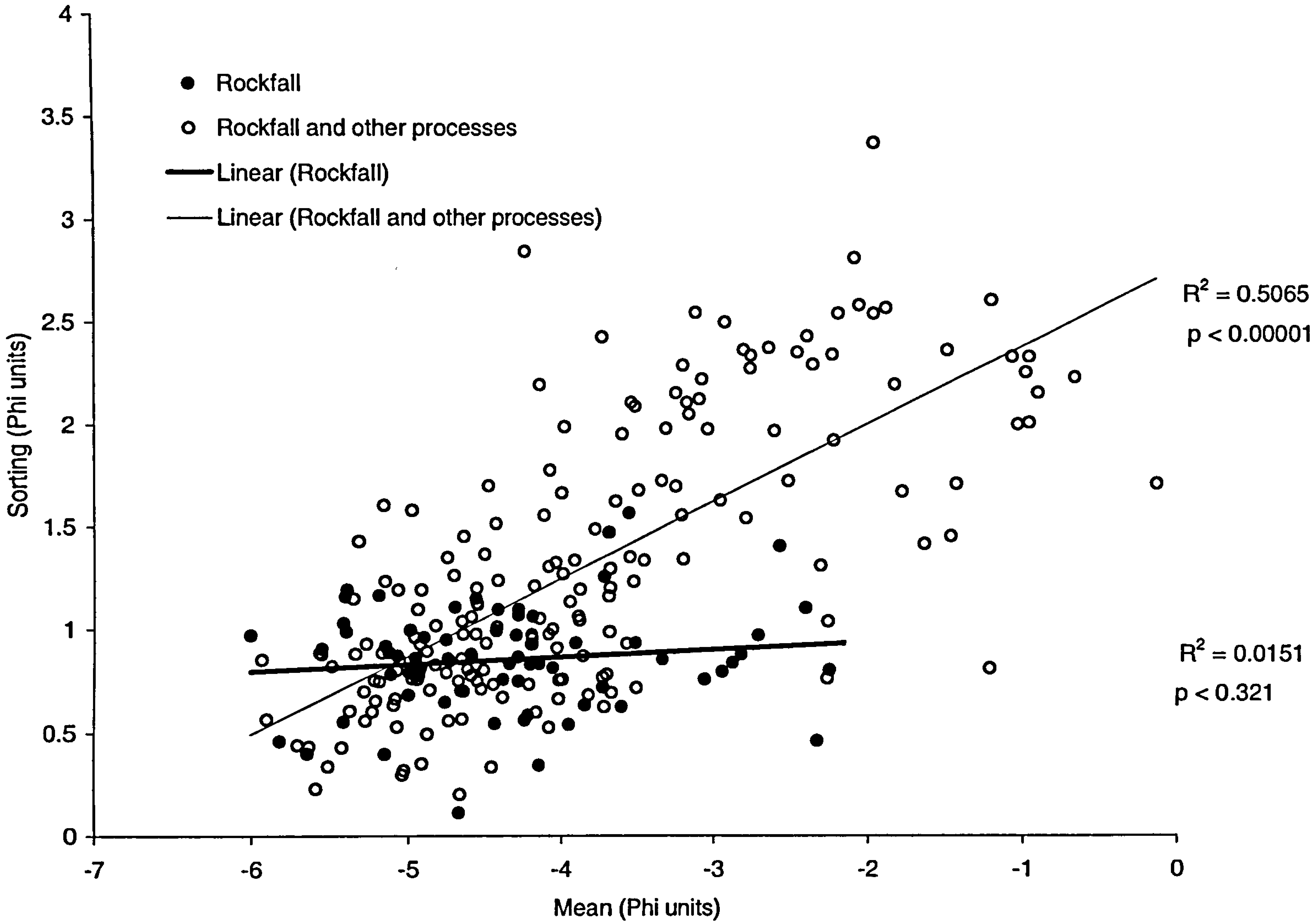


Figure 4.14: Mean particle size and sorting distinguishing between nets collecting just rockfall and those collecting sediment from other processes as well.

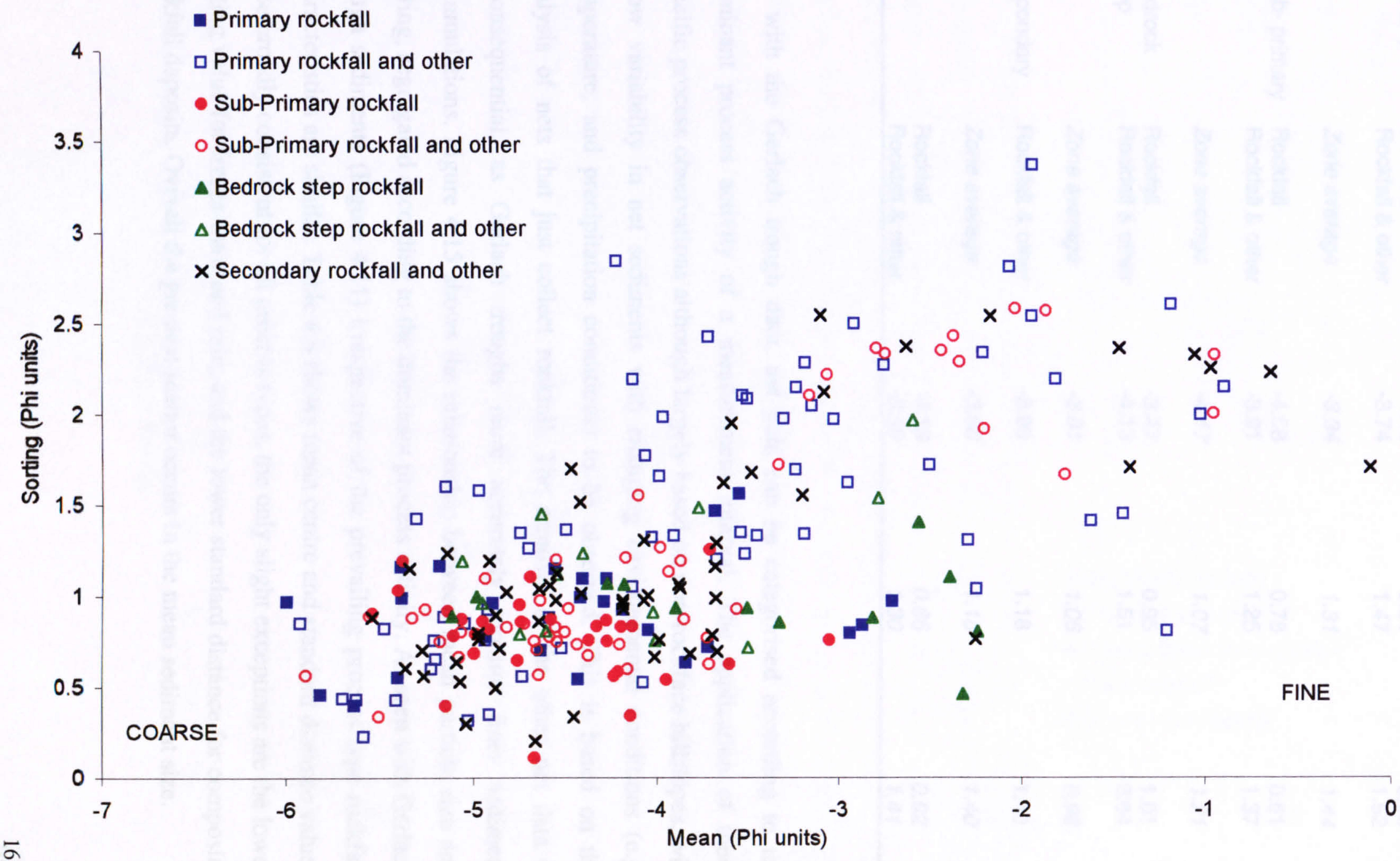


Table 4.7: Mean centre and standard distance values for data contained within Figure 4.14. (Zone averages calculated from raw data).

Zone	General process type	Mean centre (X -Mean) ϕ	Mean centre (Y- Sorting) ϕ	Standard distance ϕ
Primary	Rockfall	-4.45	0.91	0.93
	Rockfall & other	-3.74	1.47	1.52
	Zone average	*-3.94*	*1.31*	*1.44*
Sub- primary	Rockfall	-4.58	0.78	0.61
	Rockfall & other	-3.91	1.25	1.37
	Zone average	*-4.17*	*1.07*	*1.21*
Bedrock step	Rockfall	-3.47	0.95	1.01
	Rockfall & other	-4.13	1.51	0.84
	Zone average	*-3.81*	*1.06*	*0.98*
Secondary	Rockfall & other	-3.90	1.18	1.40
	Zone average	*-3.90*	*1.18*	*1.40*
All	Rockfall	*-4.33*	*0.86*	*0.92*
	Rockfall & other	*-3.86*	*1.30*	*1.41*

As with the Gerlach trough data, net data can be categorised according to the dominant process activity of a measurement interval. The application of these specific process observations although largely based on non-rockface hillslopes, will allow variability in net sediments with changing environmental conditions (e.g. temperature, and precipitation conditions) to be observed. This is based on the analysis of nets that just collect rockfall. The removal of the other net data is inconsequential, as Gerlach troughs more accurately monitor finer sediment accumulations. Figure 4.15 shows the relationship between mean particle size and sorting, segregated according to the dominant process activity. As seen with Gerlach trough sediments (Figure 4.11) irrespective of the prevailing process type rockfall characteristics are similar. Table 4.8 shows mean centre and standard distance values to be broadly consistent for all process types, the only slight exceptions are the lower sorting value for freeze-thaw and rain; and the lower standard distance for composite rockfall deposits. Overall the greatest scatter occurs in the mean sediment size.

Figure 4.15: Mean particle size and sorting, for each net deposit collecting just rockfall fragments, with segregation according to dominant process activity

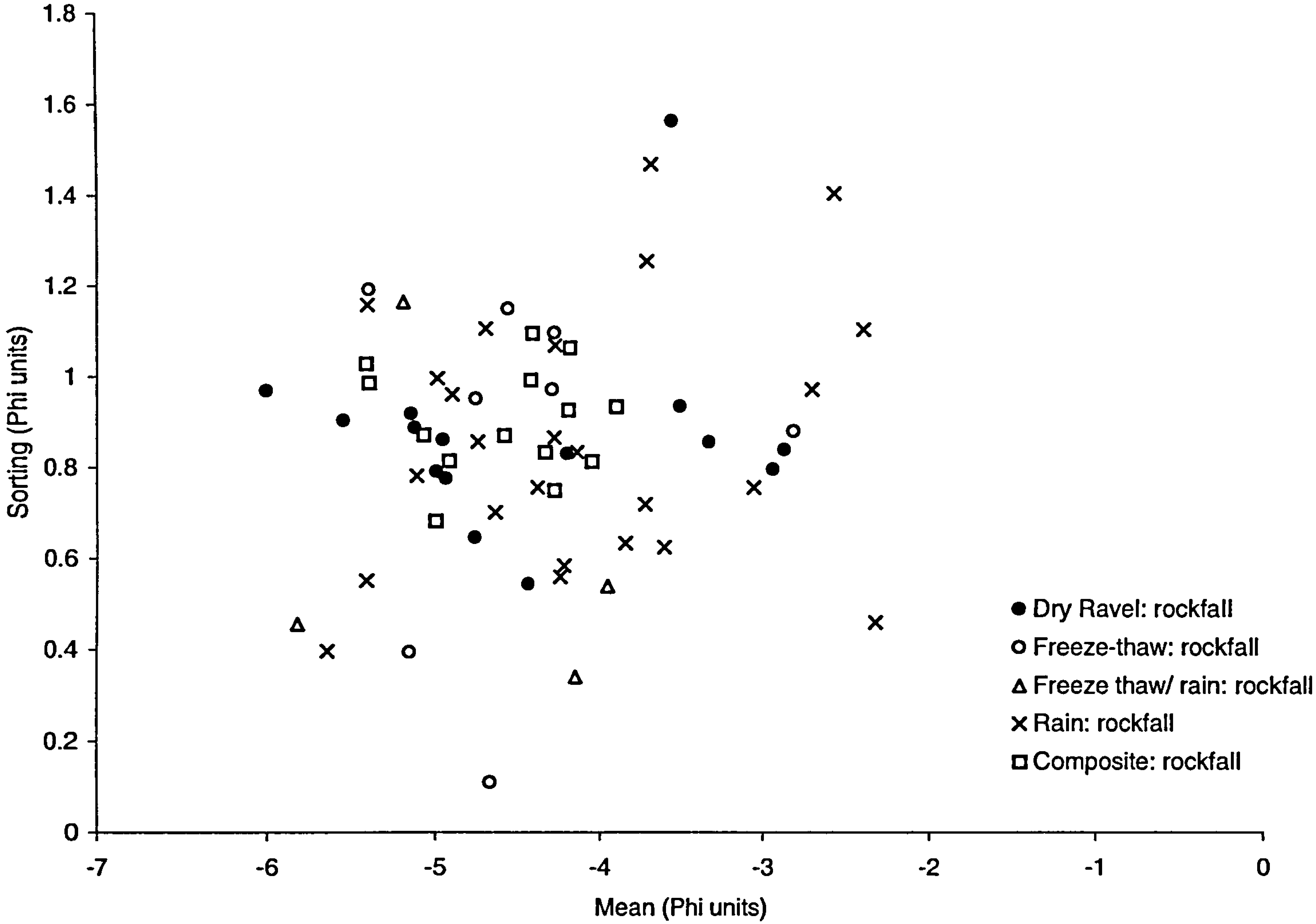


Table 4.8: Mean centre and standard distance values for data contained within Figure 4.15.

Process type	Mean centre (X- Mean) ϕ	Mean centre (Y- Sorting) ϕ	Standard distance ϕ
Dry Ravel	-4.42	0.88	0.96
Freeze-thaw	-4.49	0.85	0.81
Freeze-thaw and rain	-4.77	0.63	0.83
Rain	-4.11	0.87	0.97
Composite	-4.58	0.91	0.49

To provide greater understanding of the variability within Figure 4.15 data are segregated according to zone (Figure 4.16, Table 4.9). Unlike Gerlach troughs (Figure 4.11) net sediments appear less influenced by sediment source. As previously stated both primary and sub-primary deposits are most similar, and contrast slightly with bedrock step sediments which are finer. In the case of the primary and sub-primary zones the coarsest sediment occurs in freeze-thaw and freeze-thaw rain periods, which generally correspond with better sorting as well. These process types also have some of the tightest clustering, shown by the lower standard distance values, a finding which is concurrent with those achieved for Gerlach troughs. In a similar vein sediments associated with rainfall are again on the whole the least clustered deposits. In the bedrock step zone, composite process activity shows the coarsest (-4.04 ϕ) sediment and is the worst sorted (1.00 ϕ).

Figure 4.16: The variability of net sediments in source zones, categorised according to the dominant process type

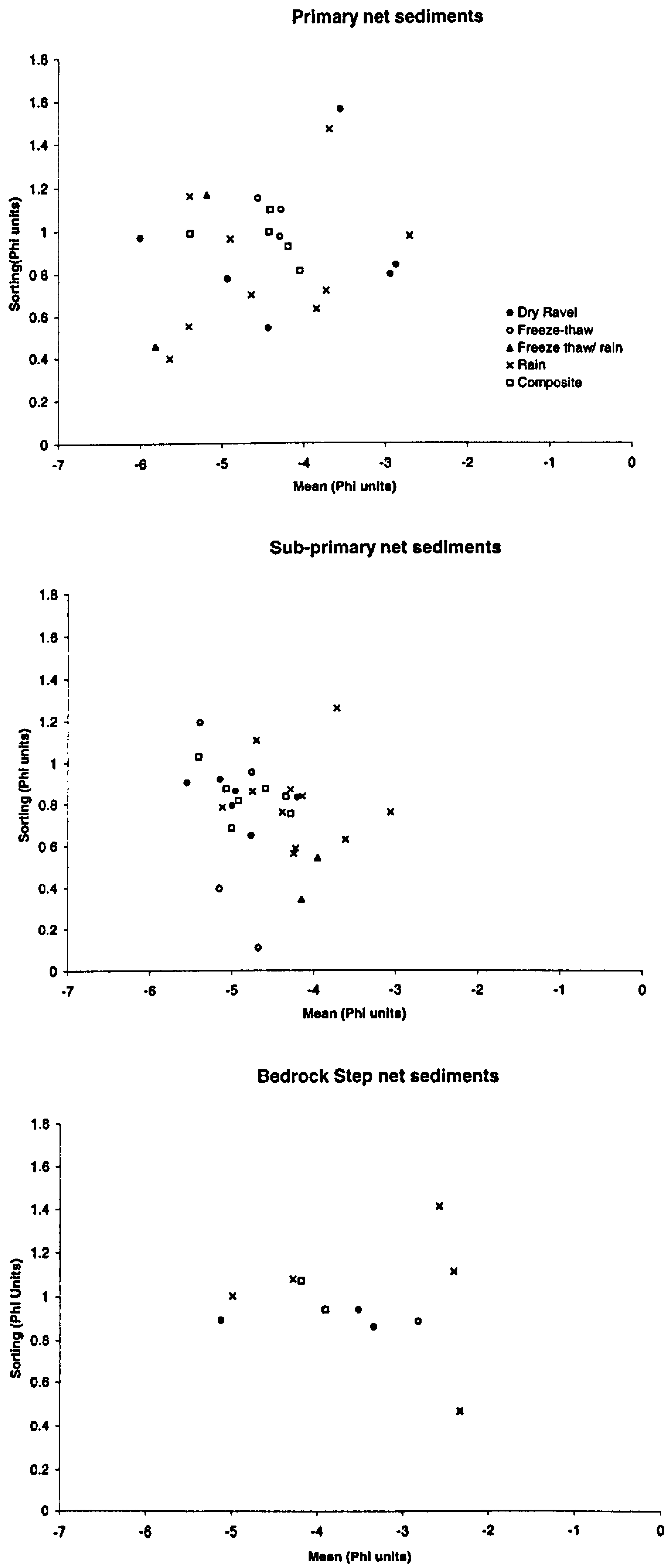


Table 4.9: Mean centre and standard distance values for data in Figure 4.16 (Zone averages calculated from raw data). (*- No standard distance value as only one data point)

Zone	Dominant process type	Mean centre (X- Mean) ϕ	Mean centre (Y- Sorting) ϕ	Standard distance ϕ
Primary	Dry ravel	-4.12	0.92	1.17
	Freeze-thaw	-4.38	1.08	0.15
	Freeze-thaw +rain	-5.50	0.81	0.48
	Rain	-4.44	0.84	0.99
	Composite	-4.49	0.97	0.48
	Zone average	*-4.45*	*0.91*	*0.93*
Sub-primary	Dry ravel	-4.93	0.83	0.42
	Freeze-thaw	-4.99	0.66	0.52
	Freeze-thaw +rain	-4.05	0.44	0.14
	Rain	-4.20	0.82	0.58
	Composite	-4.80	0.84	0.40
	Zone average	*-4.58*	*0.78*	*0.61*
Bedrock step	Dry ravel	-3.99	0.89	0.80
	Freeze- thaw	-2.81	0.88	- (*)
	Rain	-3.31	1.01	1.15
	Composite	-4.04	1.00	0.16
	Zone average	*-3.58*	*0.97*	*0.98*

Finally Figures 4.17 and 4.18 illustrate the temporal variability in zone-averaged values of sorting and mean particle size in the measurement intervals respectively. Figure 4.17 broadly shows that all values fluctuate slightly until a convergence occurs on the 16th August 1999. Prior to this point the primary zone is stable between February and March 1999, then sorting improves (values decline) into the summer. The sub-primary zone is virtually constant throughout the first six months of monitoring, whereas the bedrock step zone is most variable. Following the convergence point sorting is very variable in all zones, in general the primary and sub-primary decline and the bedrock step increases. Figure 4.18 considers mean particle size, and the overall trends are similar to those for Gerlach trough sediments that exhibit a seasonal cycle. Prior to the 25th July 1999 differences in the behaviour of sediment size over time between zones is most apparent. The primary zone gradually releases smaller sized fragments until the 12th July 1999. The sub-primary remains relatively constant, whilst the bedrock step shows a general coarsening in

Figure 4.17: Temporal variability in sorting of rockfall only net sediments

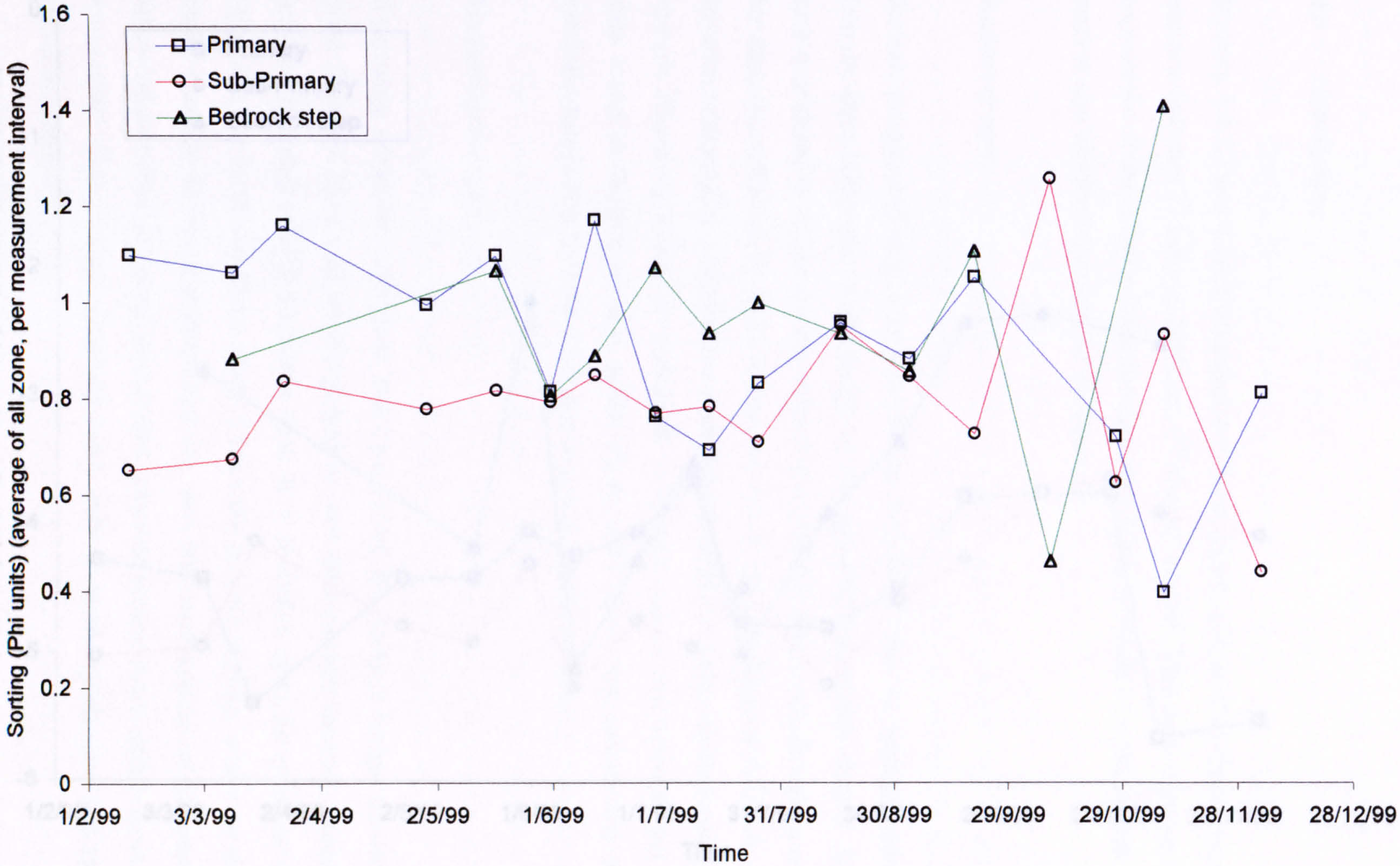
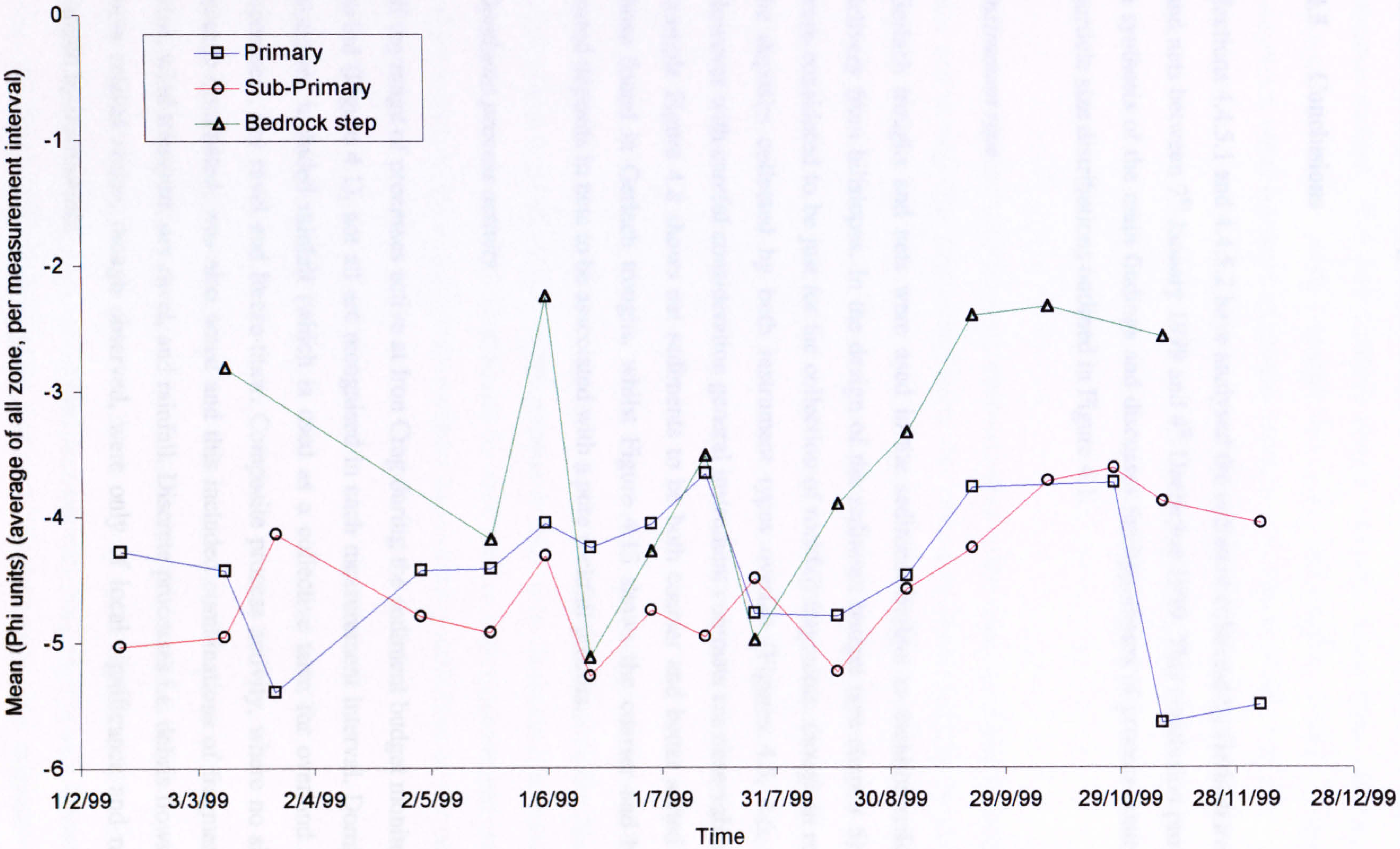


Figure 4.18: Temporal variability in the mean size of rockfall only net sediments



sediment size. After the 25th July all zones express a fining of sediment throughout August and September 1999. A short period of stability is followed by a decline towards November 1999, echoed by the coarsening of sediment towards winter as seen in the Gerlach troughs.

4.5 Conclusions

Sections 4.4.5.1 and 4.4.5.2 have analysed the sediment collected by Gerlach troughs and nets between 7th January 1999 and 4th December 1999. This conclusion provides a synthesis of the main findings and discusses the hypotheses of process controlled particle size distributions outlined in Figure 4.1.

Instrument type

Gerlach troughs and nets were used in the sediment budget to monitor sediment delivery from hillslopes. In the design of the sediment budget (see chapter 5) nets were considered to be just for the collection of rockfall fragments, though in reality the deposits collected by both instrument types overlap (Figures 4.5, 4.6, 4.7). However with careful consideration general instrument contrasts are observable. For example Figure 4.8 shows net sediments to be both coarser and better sorted than those found in Gerlach troughs, whilst Figure 4.13 shows the coarser and better sorted deposits in nets to be associated with a pure rockfall process.

Dominant process activity

Of the range of processes active at Iron Crag during the sediment budget monitoring period (Figure 4.1), not all are recognised in each measurement interval. Dominant processes included rainfall (which is used as a collective term for overland flow processes), dry ravel and freeze-thaw. Composite process activity, where no single process dominated, was also noted and this included combinations of fragmenting crust, wind transport, dry ravel, and rainfall. Discrete processes i.e. debris flows and snow related slides, though observed, were only of local significance and rarely trapped by instruments.

When bi-variate relationships between mean particle size and sediment sorting are classified according to the dominant process activity, they show a similar range in variability (Figure 4.11, Figure 4.15). The greatest variability between process types is the extent of internal scatter (relative variability), as measured by the standard distance statistic. With both Gerlach troughs and nets, freeze-thaw sediments are amongst the least variable, though this does vary slightly between zones, as sometimes other dominant processes produce less scatter (Table 4.6, 4.9). In the primary zone freeze-thaw sediments are closely clustered for both instrument types. However in the sub-primary zone freeze-thaw is no different from other process types. In the secondary zone Gerlach troughs again show less scatter in freeze-thaw derived sediments.

Rainfall-dominated measurement intervals produce the most variability in sediment size and sorting. The only exception to this rule is sediment collected by Gerlach troughs in the sub-primary zone. Relationships between particle size characteristics and rainfall intensities show a fining of sediment with increasing intensity (Figure 4.12). This is contrary to the hypothesis expressed in Figure 4.1, and suggests that either the hypothesis is invalid at this site, or more likely the processes of overland flow generation and sediment transport are more complicated than hitherto stated.

Overall the observations of the impact of dominant process activity on sediment characteristics tend to lend little support to the hypotheses discussed earlier (Section 4.4.1). There is a lack of clear differentiation in relation to dominant processes, and the absence of parent material sediment for each zone in each measurement interval makes a comparison to an initial condition beyond the possibilities of the current data set.

Sediment source variability

The division of sediment characteristics according to zone (i.e. primary, sub-primary, bedrock step and secondary) provides an illustration of the spatial variability of the impact of individual process types in the Iron Crag system (Figure 4.11- Gerlach troughs). Figure 4.16 shows net rockfall deposits vary only slightly as a function of sediment source. This may suggest that rockfall sized fragments originate from rockfall masses with similar characteristics, for example joint size and density; this is consistent with the fact that the primary and sub-primary zones are situated very close to one another. These findings suggest that sediment source exerts stronger control on trapped sediment than do different processes.

Seasonality

As the data collected in this study run from the 7th January 1999 (measurement interval 5 start) to 4th December 1999 (measurement interval 22), a complete seasonal cycle is not presented. However, one cycle is not always a sufficient basis from which to draw conclusions about seasonal impacts on the particle characteristics of sediment yield. Despite the cycle being incomplete, it does run for over 11 months. In the case of both Gerlach troughs and nets the overall trend is coarser sediment in the winter and spring months potentially reflecting active sediment production, followed by a fining in late summer and autumn (Figures 4.9, 4.10, 4.17 and 4.18). This fining process is consistent with the seasonal cycle of hillslope sediment yield identified in Chapter 5. A coarsening of the particle size occurs in the Gerlach trough and net sediments during November and December 1999, which marks the onset of freeze-thaw activity. Hence a seasonal cycle of coarse sediment production and exhaustion appears to exist. The implication of this finding is that the sequence of process activity may impart a long-term control on the characteristics of sediment sources, and therefore the impact of individual processes is subject to this inheritance.

Why does process activity fail to behave as hypothesised?

For Gerlach troughs a potential answer may be that the concept of a dominant process activity for each measurement interval is too broad and ignores the fact that more than one process may be responsible for the collected deposit. An alternative answer is that the slopes are steep at Iron Crag, thus all sediment is easily entrained and transported. Thus the different entrainment and sorting abilities associated with different process types becomes less important, as all processes trigger the removal of sediment under the influence of gravity. In the case of the net rockfall deposits the lack of difference between dominant processes and thus environmental conditions, may reflect the fact that rockfall fragment size is dominantly controlled by source variables.

Improvements for study of process related sediment characteristics

To test the conclusions of this study in a field environment, more rigorous and detailed monitoring of sediment delivery is required. Developments should include:

1. A sample of local source material for each instrument in each measurement interval. This will establish the changing nature of source sediments spatially and temporally. Though it is important to minimise the disturbance of the sediments associated with this sampling design.

2. To avoid the need to decide on 'dominant' process activity measurement intervals should be more frequent, preferably following each individual sediment delivery event.

3. Instrument positioning should further attempt to limit interference from multiple processes.

Finally, because of the use of graphical statistics, the preceding analysis has been carried out in a phi ($-\log_2$ mm) units. The significance of the log scale should always be considered when interpreting differences in the results.

CHAPTER 5: SEDIMENT BUDGET OF AN ACTIVE TORRENT SYSTEM

5.0 Scope and aims

This chapter presents the results of sediment budget monitoring in the Iron Crag torrent, northern Lake District. It investigates the processes involved in torrent erosion; evaluates the importance of particular components of the sediment system; and describes spatial and temporal variability of processes within different zones. Section 5.1 outlines the general methodology used to construct the sediment budget. The main body of the investigation is in section 5.2, which considers the annual sediment budget (section 5.2.1), the temporal variability of sediment budget components (section 5.2.2), and the impacts of particular meteorological events on the system (section 5.2.3). Section 5.3 investigates bedload movement. Finally, section 5.4 summarises the key findings and provides recommendations for improved measurement techniques in light of this research.

This chapter quantifies torrent erosion in a steep Lake District mountain catchment, (Iron Crag), over a 12-month period. In pursuing this general aim a number of specific objectives are defined:

1. Construct a sediment budget for the torrent system in order to quantify the main geomorphological processes. This will reveal the spatial variability of sediment production, transport, and storage, allowing the importance of particular zones within the system and process components to be identified.

2. Describe temporal variability of process activity and seek explanation for the observed patterns.

3. To define how different meteorological conditions impact on the operation of torrent erosion in the Iron Crag system.

5.1 Methodology

The sediment budget of the Iron Crag system was developed using the guidelines of Reid and Dunne (1996). They outline a procedure for the construction of a sediment budget, composed of seven main steps. These include definition of the problem; acquisition of background information; subdivision of the study area; interpretation of aerial photographs; conducting fieldwork; analysis of data; and finally the checking of results.

5.1.1 Planning phase

Initial field reconnaissance determined that the Iron Crag sediment system could be separated into three basic morphological-process zones, i.e. hillslopes, channel and basal fan. Sediment transfer within and between these zones became the focus of the investigation. It was also observed that different meteorological events appeared to influence the geomorphological responses of the system in different ways.

Following the precept of Reid and Dunne (1996, p13) that *"every project area is too large and too complex"*, the three main zones at Iron Crag were further subdivided (Figure 5.1):

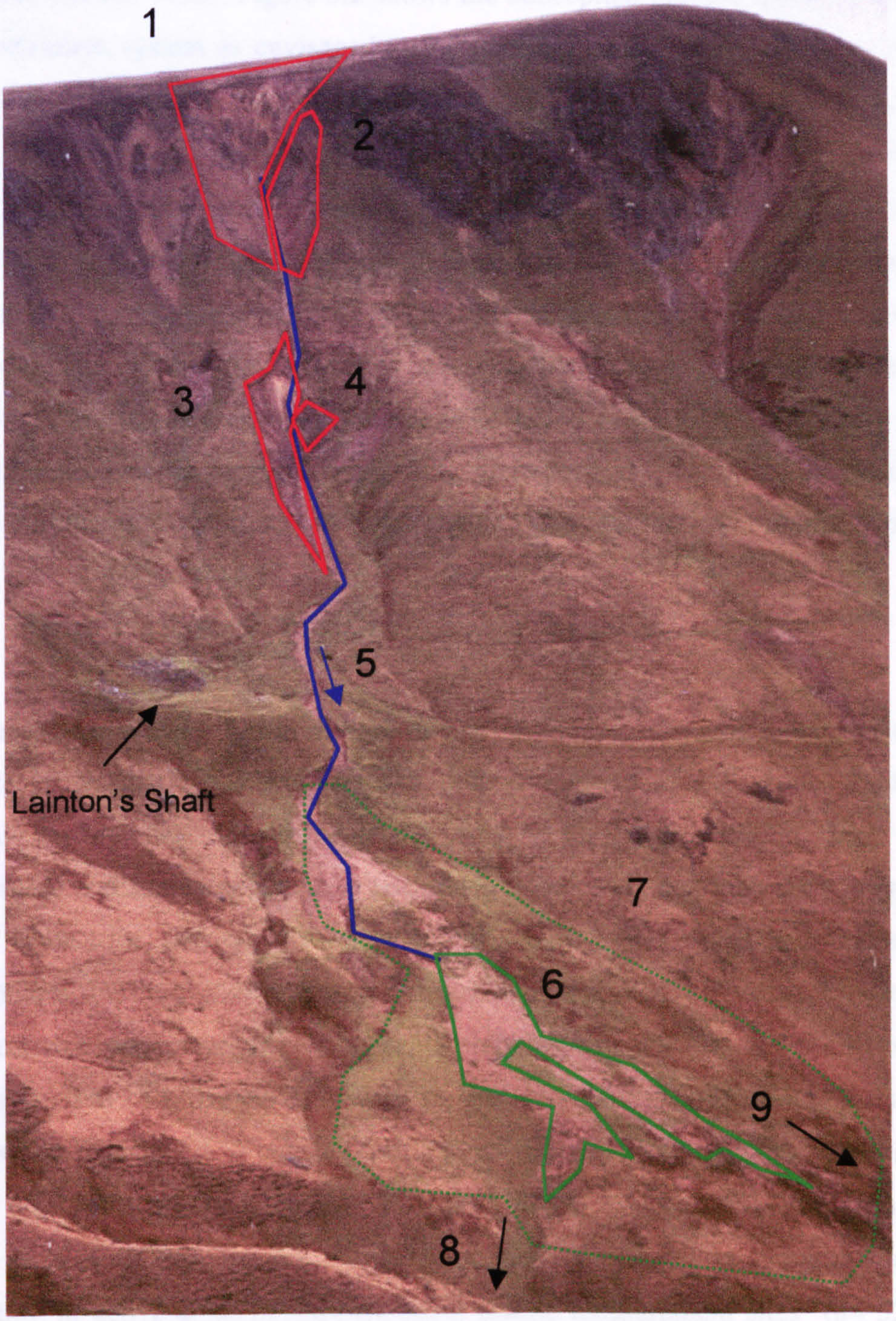
1. Hillslope sediment sources were subdivided into four areas, namely the primary zone, sub-primary zone, secondary zone, and the bedrock step outcrop zone.

2. The channel system is considered as a single zone. At the distal end of the confined channel is a fan that is treated as a separate zone.

3. Beyond the fan are two infilled reservoirs associated with historical mining activity.

4. Finally a small ephemeral tributary links the fan to Todd Gill (tributary of Dale Beck). There is little apparent coarse sediment transfer between the two.

Figure 5.1: Iron Crag morphological zones, superimposed on a photograph of Iron Crag taken from Peteraw (500m O.D. NY 304 348)



1:Primary hillslope zone
2:Sub- primary hillslope zone
3:Secondary hillslope zone
4:Bedrock step hillslope zone
5:Channel
6:Active fan deposit
7:Overall fan area
8:Exit to Todd Gill
9:Mine reservoirs

In each of these zones active processes were identified on the basis of direct field observation and background knowledge of process activity (e.g. Caine and Swanson, 1989; Warburton, 1990; Sutherland and Bryan, 1991; Vandaele and Poesen, 1995; Reid and Dunne, 1996). Figure 5.2 shows the conceptual process model of the Iron Crag sediment system as envisaged at the planning phase of the sediment budget. Based on Figure 5.2 a measurement framework was planned to investigate: soil creep, sheetwash, rill erosion, rockfall, slope erosion, bank erosion, channel bed change, channel planform change, fan sedimentation, and basic meteorological conditions. Table 5.1 indicates the measurement and monitoring strategies that were adopted in this study (Appendix 5.1 outlines the design of the instruments and survey methods). Not all the data collected are incorporated into the sediment budget analyses. This is because certain instruments failed to perform adequately, had a poor spatial coverage, or were duplicating measurement made more accurately by other instruments. Specific cases of data exclusion are outlined later in this chapter.

5.1.2 Design and operation of the measurement framework

The next stage was to decide on the number and siting of instruments required to achieve representative measurement of process activity in each zone. Table 5.2 outlines the number of instruments installed in each zone. Within these zones instruments and survey points were positioned to achieve good spatial coverage, but at the same time seeking a balance between maximising detail and minimising disturbance. Further, instruments were positioned at key locations, to intercept sediment transport paths. For example, Gerlach troughs (n= 13) are placed on un-vegetated areas of hillslope dominated by granular material, which is the material size they are designed to collect. Troughs are distributed throughout all hillslope zones, e.g. in the primary zone one or more Gerlach troughs are within each head gully. Nets (n= 22) are located beneath rock crags, within gullies and at the base of hillslopes, in active areas of rockfall. Bank profile measurement sites (n= 52) are located on both sides of the channel, before, at and after channel bends. The greatest density of measurements is found in the lower part of the channel (from the secondary hillslope zone downwards) as it is in this reach that banks are larger and undergoing more frequent change. Eleven micro cross sections locations were established to observe changes in the channel bed. The peg array (n= 126), on the fan

Figure 5.2: Conceptual model of the Iron Crag sediment system (pre sediment budget) [Open boxes: process activity; Shaded boxes: material sources and stores; ellipse: output]

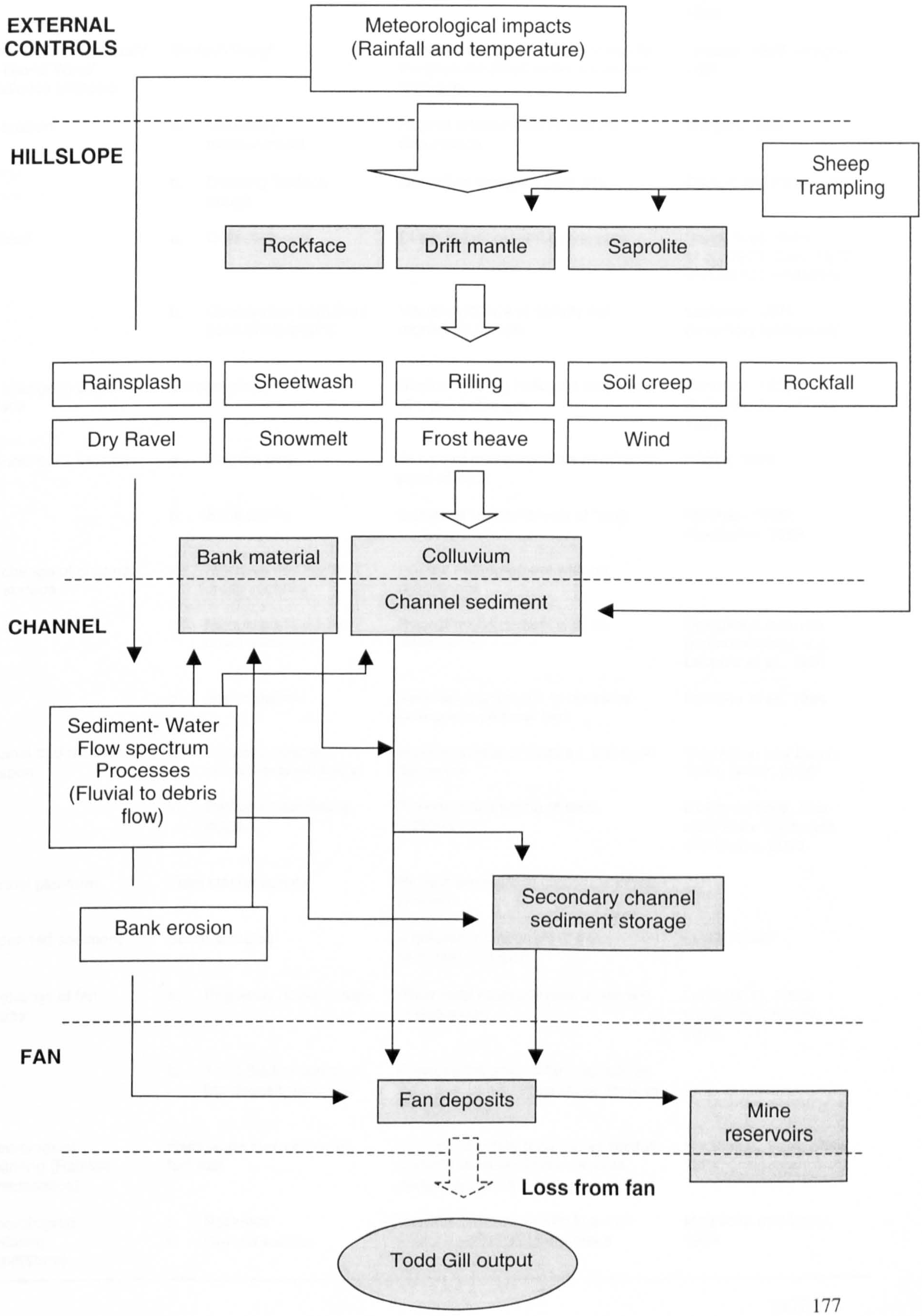


Table 5.1: Measurement and monitoring approaches applied to sediment budget at Iron Crag

Process/ attribute	Approach	Justification	Past application (Example)
Soil creep	Flexible tube insert	Permanent, and minimal disturbance	Carson and Kirkby, 1972; Fleming and Johnson,1975; Statham, 1990
Sheetwash/ Rainsplash/ Dry Ravel/ Wind/ Needle-ice collapse	Gerlach trough	Effective design of sediment trap for the granular sized sediment on the hillslopes	Gerlach, 1967; Morgan 1995
Rill erosion	a. Geometry measurement	Repeat measurements with no disturbance	Morgan, 1995
	b. Draining Gerlach trough	Quantifies transport from rills	Carson and Kirkby, 1972
Rockfall	a. Collecting nets	Direct measurement by trapping	Rapp, 1960; Prior *et al.*, 1971; Gray, 1972 (Debris accumulation)
	b. Observation from fixed point photographs	Visual evidence of activity not monitored by nets	Luckman, 1976 (Inventory techniques)
Net change in slope surface	Erosion pins	Statham (1990) indicates they show at-a point changes	Schumm, 1956; Sutherland and Bryan, 1991
Channel bank erosion	a. Erosion pins	At a point measurements at different point of bank	Hooke, 1979
	b. Bank profile	Complete measurement of bank	Wolman, 1959; Warburton, 1989
Net change of channel bed surface	a. Monumented macro cross sections	Repeat measurement with no disturbance	
	b. Monumented micro cross sections	Repeat measurement with no disturbance	Ubiquitous in fluvial geomorphology, e.g. Leopold *et al.*, 1964
	c. Scour chains	Alternative approach to measure changes in channel bed	Laronne *et al.*, 1994
Channel bed material transport	a. Painted/ magnetic natural bedload tracer	Provide details of bedload transport dynamics	Warburton and Demir, 1998; Demir, 2000
	b. Bedload clast timing logger	Provide exact timing of clast mobilisation	Designed here, also applied by Warburton and Evans, 2000
Channel planform	Total station survey	Provide measure to identify planform change	
Suspended sediment	Bottle samples	A different component of the sediment transport	Lewin, 1990
Net change of fan Surface	a. Peg array (stake array)	Allow local measurement of erosion or deposition	Lehre *et al.*, 1983; Carson and Kirkby, 1972.
	b. Total Station survey of fan deposit perimeter	Provides the area of fan deposit, so indicates activity beyond the limits of the peg array	
Meteorological monitoring (Rainfall characteristics)	Raingauge surrounded by turf wall	Site specific data required as rainfall spatially variable. Shows events system subject to.	Hudleston, 1934; Shaw, 1994
Meteorological monitoring (temperature)	a. Rockface b. Ground surface	Records thermal activity in a rock fracture and at ground surface	Matsuoka and Sakai, 1999

Table 5.2 : Zone processes and monitoring details

Spatial zone	Process/ attribute	Instrument/ survey	Number
PRIMARY	Sheetwash etc.	Gerlach troughs	7
	Rockfall	Fixed point photography of crag Nets	5 photos 8
	Net change in slope surface	Slope erosion pins	52
	Creep	Flexible tube inserts	9
SUB-PRIMARY	Sheetwash etc.	Gerlach troughs	3
	Rilling	Rill geometry (cross sections) Draining Gerlach trough	4 1
	Rockfall	Fixed point photography of crag Nets	1 photo 5
	Net change in slope surface	Slope erosion pins	18
	Creep	Flexible tube inserts	9
CHANNEL	Channel bank erosion	Bank erosion pins Bank profiles	61 52
	Net change of channel bed surface	Macro cross sections Micro cross sections Scour chains	11 11 11
	Channel planform	Planform survey	2 TBM's
	Channel bed material transport	Hobo® State loggers Painted/ magnetised local bedload tracers	3 150
	Flow discharge and suspended sediment	Flow volume and bottle sample	3 collection points
SECONDARY	Sheetwash etc.	Gerlach troughs	3
	Rockfall	Fixed point photography of crag Nets	5 photos 6
	Total slope denudation/ colluvium accretion	Slope erosion pins	24
BEDROCK STEP	Rockfall	Fixed point photography of crag Nets	3 photos 3
FAN & INFILLED RESERVOIRS	Net change of fan surface	Peg array Survey	126 1 TBM
METEOROLOGICAL MONITORS	Ground temperature	Hobo® Temp logger	1
	Rock face temperature	Hobo® Temp logger	1
	Rainfall	Hobo® Event logger & Rainwsise ® Inc.Rainew-100	1+1

surface, is concentrated in areas of current sedimentation (un-vegetated deposits), although a number of pegs are also located in adjacent vegetated areas to record any new sedimentation.

Following the initial installation (October-November 1998) instrument performance was monitored over a month. This period revealed 'teething' problems in the experimental design which were rectified before full scale monitoring began. Problems with Gerlach troughs, nets and the timing logger were resolved. Gerlach troughs tended to be blown or knocked off their fixing pegs, and therefore failed to trap sediment. A counter measure that proved effective was to use longer metal fixing pins and attach the Gerlach trough to the metal pins with plastic grip ties. In a few cases further pins were placed on the downslope side of the trough to provide more support. To increase sampling efficiency the upper plates of the troughs were bent upwards in the field, increasing the size of the entry aperture between the metal lip plates. Overflow bottles collected negligible amounts of sediment, therefore it was decided to collect the trough sediment trapped and abandon the overflow devices. Nets, like Gerlach troughs, became detached. This was significantly reduced by pinning down the nets with more metal pegs, and bent 'U' shaped pins. Nets too close to channel margins suffered disturbance from channel, to prevent this nets were moved upslope of the channels where possible. The clast timing logger devices suffered corrosion of the wire circuits, initially due to water, then in a revised design due to acetic acid in the sealant. Also sheep nibbled through any unprotected wire. All these problems were rectified, and a fourth version of this device was fully operational later in the sediment budget.

After rectifying the initial problems the sediment budget study became fully operational in December 1998. At this point it was decided that it was impracticable to tend to all instruments and surveys on every visit to Iron Crag. Therefore a framework for monitoring was established as outlined in Table 5.3.

Table 5.3: Iron Crag measurement intervals and common sampling and downloading practices.

Measurement Interval	Instruments/ and surveys used	Action
Normal	Gerlach Trough	Empty, clean, refit
	Net	Empty, check fixing
	Slope erosion pin	Measure exposure length
	Rill geometry	Measure cross section profile
	Channel erosion pin	Measure exposure length
	Scour chain	Measure exposure length
	Micro channel cross section	Measure cross section profile
	Peg array	Measure exposed height
	Suspended sediment concentration	Sample water
	Water Discharge	Measure
	Qualitative observations	Note change and process activity
	Clast loggers	Check look okay, download if tripped. If so, return to Durham for rebuild
Quarterly/ Storm	*As above with the addition of:*	
	Fixed point Photography of crags	Observe and record fresh failures
	Bank profiles	Measure profile, check marker pin
	Bedload Tracer	Measure clast location
	Planform survey	Total station survey
	Fan deposit survey	Total station survey
Monthly	Rainfall data	Download data and reset logger
	Temperature data	Download data and reset logger
One-off	Mapping of spatial zones and instrument location within these.	Total station survey
	Catchment area of nets and troughs	Total station survey of areas.
	Creep tubes	Extract tube after setting

Table 5.3 shows that some measurements were made regularly, whilst others were done every quarter or immediately following a major event in the system. Normal measurements were undertaken every 2 to 3 weeks where possible, and included those tasks which could be completed in one day, and which formed the focus of the sediment budget, i.e. slope sediment production (Gerlach trough, nets), channel change (micro cross sections), and fan surface change (peg array). Taking measurements from these instruments on a regular basis gave the sediment budget a detailed temporal resolution. An interval of several weeks was found to be acceptable as the capacity of the nets and Gerlach troughs was rarely exceeded. Quarterly and storm measurements took between 4 and 14 days to complete depending on the event and logistics. Some measurements were inevitably interrupted owing to weather conditions and equipment failures, though the majority of measurements were made in a sustained spell of fieldwork. In addition to this two-tier strategy the meteorological loggers were downloaded approximately every month. Whilst capable of holding more data, it was considered safer to download data frequently and correct any problems which developed. Also mapping of the

system was undertaken in one survey. This provided information on the system zones, showed the location of the instruments and marker pegs, and helped define the catchment areas of nets and Gerlach troughs.

Reid and Dunne (1996) state that the data collected for a sediment budget are at different scales and in many formats, and therefore need to be reconciled into a common format, and be spatially and temporally comparable. This was indeed the case with the data collected at Iron Crag. What follows is an outline of the general structure of the data selected for use in this study, i.e. units of measurement, spatial scaling, and temporal averaging.

The fundamental unit of measurement for the sediment budget is mass (measured in metric tonnes). At Iron Crag only a limited amount of data were collected with units of mass, the majority of measurements were in metric units of distance, area and volume. Using bulk density values (t m^{-3}), it is possible to convert volume measurements into mass. In this conversion small changes in the density can strongly alter the computed mass. Therefore the density values were chosen carefully, being calculated from multiple samples of material from the channel bed (n=30), the channel banks (n=10), and the fan surface (n=9) (Table 5.4). The channel bed samples were obtained from a combination of material deposited behind a v-notch weir built in the channel after the main sediment budget period; and from channel bed locations downstream of the weir. Channel bank samples were extracted from undisturbed bank exposures. The fan was sampled between apex and distal locations. The mean fan bulk density value (1.249 t m^{-3}) is considered precise (low standard deviation), yet inaccurate and would therefore result in an underestimated fan mass (Warburton, 2001, *pers. comm.*). This value is probably a function of both the difficulty of obtaining bulk density in the field from pits and cores, and the fact that the surface fan sediments at the time of sampling had undergone the effect of multiple freeze-thaw cycles which loosen the sediment structure. Samples should have been excavated from greater depth, but unfortunately large pits were not permitted. Therefore the channel bulk density value (1.871 t m^{-3}) is considered a more accurate bulk density value for the fan sediments, as it these sediments that accrete on the fan surface.

Table 5.4: Bulk density values for Iron Crag channel and bank sediments.

Sediment type	Volume (Litres)	Volume (m^3)	Mass (kg)	Bulk density ($t\ m^{-3}$)	Mean Bulk density	Standard deviation
Channel	13		24.5	1.885		
(n = 30)	13		25	1.923		
	13		24.5	1.885		
	13		24.5	1.885		
	13		24.75	1.904		
	13		25	1.923		
	13		30	2.308		
	13		20	1.538		
	12		23	1.917		
	12		21.5	1.792		
	12		19	1.583		
	12		21.5	1.792		
	12		22.5	1.875		
	12		23.5	1.958		
	12		24	2.000		
	12		24	2.000		
	12		23.5	1.958		
	12		20	1.666		
	12		24	2.000		
	12		25	2.083		
	12		26	2.166		
	12		25	2.083		
	12		25	2.083		
	12		21	1.750		
				1.709		
		0.003174	3.65	1.150		
		0.010692	20.4	1.908		
		0.007590	12.4	1.634		
		0.017138	31	1.809		
		0.006534	12.90	1.974	**1.871**	**0.217**
Banks		0.002250	2	1.866		
(n =10)		0.002393	4.2	1.755		
		0.001584	3	1.894		
		0.005434	7.25	1.334		
		0.004446	7.3	1.642		
		0.002550	5.1	2.000		
		0.001995	3.1	1.550		
		0.002520	4.1	1.627		
		0.005733	8.9	1.552		
		0.003762	7.5	1.993	**1.721**	**0.218**

Measurements were made in relation to specific areas or locations. Scaling up was required to provide area weightings. For example, Gerlach troughs collect sediment from a known catchment area on the hillslope (see Appendix 5.1: 4). The mass obtained from a particular Gerlach trough was then used to estimate yields for the entire slope area. Such spatial scaling is similar throughout the sediment budget procedure, though the exact application varies according to the instrument type, the availability of data, and the exact location. In the annual sediment budget the mass values quantify the amount of sediment associated with different process activity for the year. To achieve this, the calculated masses for each measurement interval are summed.

5.2 Sediment budget analysis

5.2.1 Calculation of the annual sediment budget

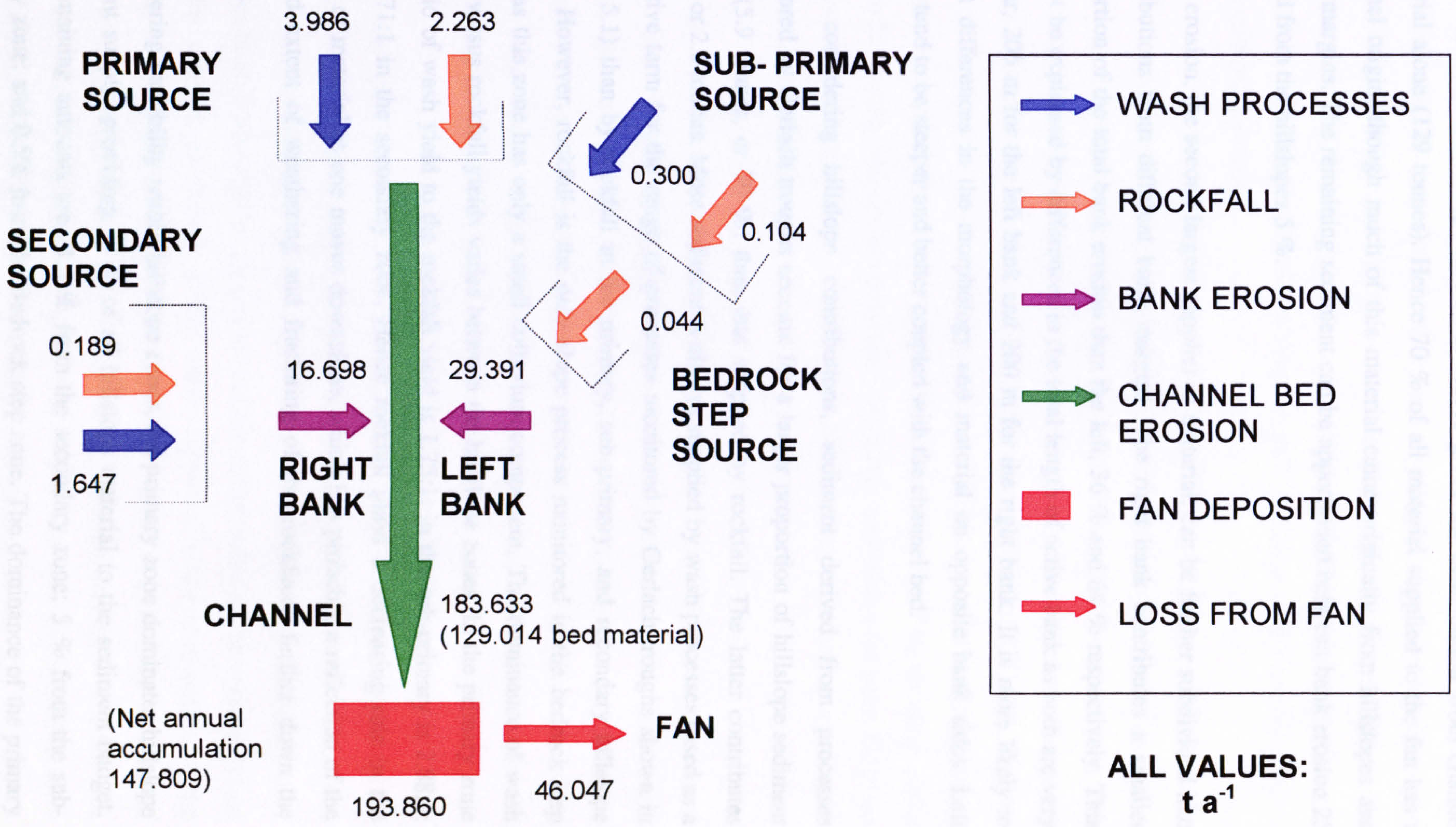
5.2.1.1 Sediment budget- December 1998 to December 1999

This section presents the annual sediment budget for Iron Crag, based on data between 12th December 1998 and the 7th December 1999 (sediment budget monitoring period). Data prior to the start of early December 1998 as previously stated were used to refine techniques and allow instruments to become established at the site after initial disturbance. Within this time series there are small breaks in the record. For example in the case of the micro cross sections it was sometimes not possible to measure the channel as it was frozen and covered in snow. Therefore changes in the channel bed are measured by the difference in the cross section taken from the last measurement prior to the ice-snow affected measurement interval, and the next following measurement. This approach may disguise some of the channel bed changes. This method is applied to the channel cross-sections, bank profile, and fan peg array data.

The second correction applied to the data is temporal scaling. This is applied because the exact periods of monitoring differ slightly between instruments, which is a consequence of the time required to conduct the measurements and the weather conditions controlling when certain measurements were made. However, the differences are negligible, and therefore the sediment budget can be considered to represent the period mid-December 1998 to mid-December 1999.

The data used in the construction of the annual sediment budget (Figure 5.3) comprise: Gerlach trough and net yields (hillslope sediment production), channel micro cross sections (channel material erosion and storage), bank profiles (bank erosion sediment yield), fan peg array and fan surveys (fan deposition and erosion). From Figure 5.3 a number of conclusions can be made about process activity during this monitoring period. First, the erosion of material from the channel bed is the dominant source of material supply to the fan. The value of 184 tonnes includes material supplied by the four hillslope zones and the channel banks. This value

Figure 5.3: Iron Crag annual sediment budget December 1998 to December 1999.



minus the sum of hillslope and bank values gives the contribution from channel material alone (129 tonnes). Hence 70 % of all material supplied to the fan has a channel origin, though much of this material came originally from hillslopes and bank margins. The remaining sediment can be apportioned between bank erosion 25 % and from the hillslopes 5 %.

Bank erosion, the second largest supplier of material, can be further subdivided into contributions from different bank margins. The right bank contributes a smaller proportion of the total bank erosion than the left, 36 % and 64 % respectively. This cannot be explained by differences in the total length of active bank as both are very similar, 206 m for the left bank and 200 m for the right bank. It is more likely to reflect differences in the morphology and material on opposite bank sides. Left banks tend to be steeper and better coupled with the channel bed.

Third, considering hillslope contributions, sediment derived from processes monitored by Gerlach troughs account for a larger proportion of hillslope sediment yield (5.9 tonnes, or 70 %) than that supplied by rockfall. The latter contributes 30 %, or 2.6 tonnes. More sediment is always supplied by wash processes (used as a collective term for the range of processes monitored by Gerlach troughs shown in Table 5.1) than by rockfall in the primary, sub-primary, and secondary hillslope zones. However, rockfall is the only slope process monitored in the bedrock step zone, as this zone has only a small colluvium component. The dominance of wash yields versus rockfall yields varies between the hillslope zones. In the primary zone the ratio of wash yield to the rockfall yield is 1.75:1; in the sub-primary is 2.88:1; and 8.71:1 in the secondary zone. Hence rockfall plays a decreasing role in the supply of material as one moves downslope, which is a probably a reflection of the reduced extent of weathering and fracturing of the rockfaces further down the system.

Considering variability within hillslope zones, the primary zone dominates hillslope sediment supply, providing 73 % of all hillslope material to the sediment budget. The remaining amounts are 21.5 % from the secondary zone; 5 % from the sub-primary zone; and 0.5% from the Bedrock step zone. The dominance of the primary hillslope source is attributed to a zone of loose colluvium and very active rilling.

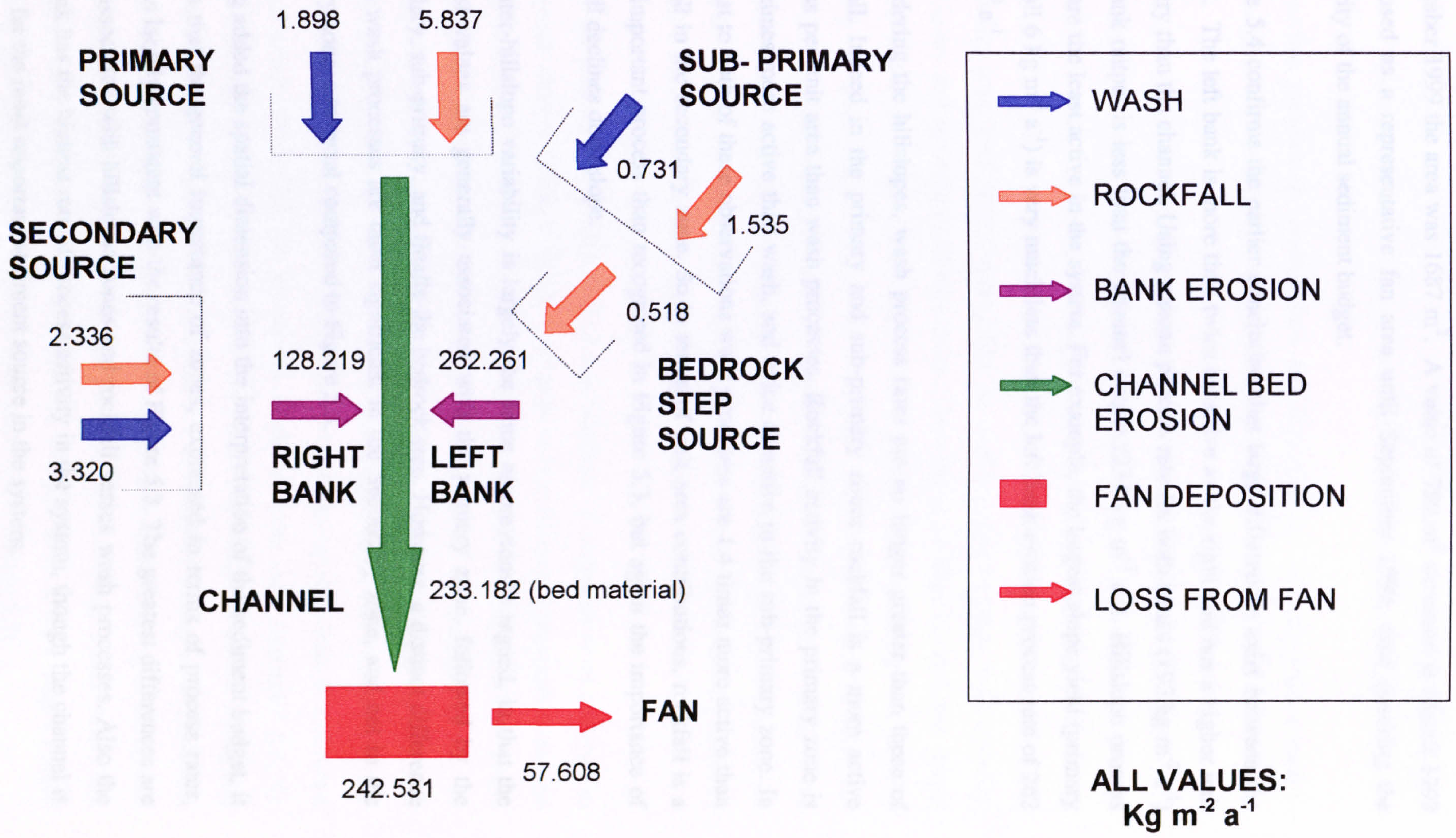
Fourth, the fan at the base of the system appears to be a net sediment sink accumulating 148 tonnes over the course of the sediment budget. This is the difference between the calculated deposition of 194 tonnes and a loss of 46 tonnes from the fan. The gross deposition value is 10.2 tonnes greater than the input of sediment from the channel.

These observations of process activity and spatial variations are based upon total yields over the year. However, they are not spatially weighted values. Introducing the spatial dimension allows area weighted process rates to be calculated. Figure 5.4 outlines process rates per unit area, expressed in terms of 'kg m^{-2} a^{-1}'. This confirms some of the previous conclusions from Figure 5.3, but in some cases presents a different perspective. Spatially weighted values are calculated by dividing yields (Figure 5.3) by the area of the source zone or process area within the zone. Hillslope areas were determined in the field using total station data and surface areas calculated in SURFER®.

The bank areas are calculated from the mean bank height of two adjacent bank profiles, multiplied by the length between the bank profiles, i.e. creating a simple polygon. Distances are measured with a total station. Bank height is determined as the vertical difference between the bank top and bank base. Where the bank profile contains concavities or departs from the vertical measurement the actual surface of the bank is greater than that expressed by the vertical distance.

The channel area is calculated from total station planform survey, splitting the channel into a number of simple polygons. Again using SURFER® the surface area of the sloping channel bed is calculated and summed to given a total channel area. This procedure is accurate for the majority of the sediment budget monitoring period when the channel planform remained static. However in the later phases of the sediment budget planform change near the fan altered the channel area, resulting in an underestimation of the area and overestimation of the process rates. The fan area underwent significant change during the period of monitoring. In September 1998 before the sediment budget began the area of fresh deposit was 777 m^2, but by

Figure 5.4: Iron Crag annual sediment budget with spatial calibration- December 1998 to December 1999.



December 1999 the area was 1687 m^2. A value of 799 m^2 surveyed in March 1999 was used as a representative fan area until September 1999, thus covering the majority of the annual sediment budget.

Figure 5.4 confirms the earlier conclusion that large differences exist between the banks. The left bank is more than twice as active as the right and has a higher unit delivery than the channel. Using a mean process rate for both banks (195 kg m^{-2} a^{-1}) the bank output is less than the channel output (233 kg m^{-2} a^{-1}). Hillslope process rates are the least active in the system. For example, the largest slope yield (primary rockfall 6 kg m^{-2} a^{-1}) is very much less than the left bank erosion process rate of 262 kg m^{-2} a^{-1}.

Considering the hillslopes, wash process rates are no longer greater than those of rockfall. Indeed in the primary and sub-primary zones rockfall is a more active process per unit area than wash processes. Rockfall activity in the primary zone is three times more active than wash, and twice as active in the sub-primary zone. In contrast to both of these observations wash processes are 1.4 times more active than rockfall in the secondary zone. So in terms of unit area contributions, rockfall is a more important process than recognised in Figure 5.3, but again the importance of rockfall declines downslope.

The inter-hillslope variability is largely the same as previously argued, in that the greatest values are generally associated with the primary zone, followed by the secondary, sub-primary, and finally the bedrock step. However, a distinct difference is that wash processes are most significant in the Secondary zone, and not in the primary zone, a reversal compared to Figure 5.3.

Having added the spatial dimension into the interpretation of the sediment budget, it is seen that the general importance of zones, expressed in terms of process rates, remains largely consistent with the results of Figure 5.3. The greatest differences are those associated with hillslopes zones and rockfall versus wash processes. Also the left bank has the highest rate of process activity in the system, though the channel is still by far the most important sediment source in the system.

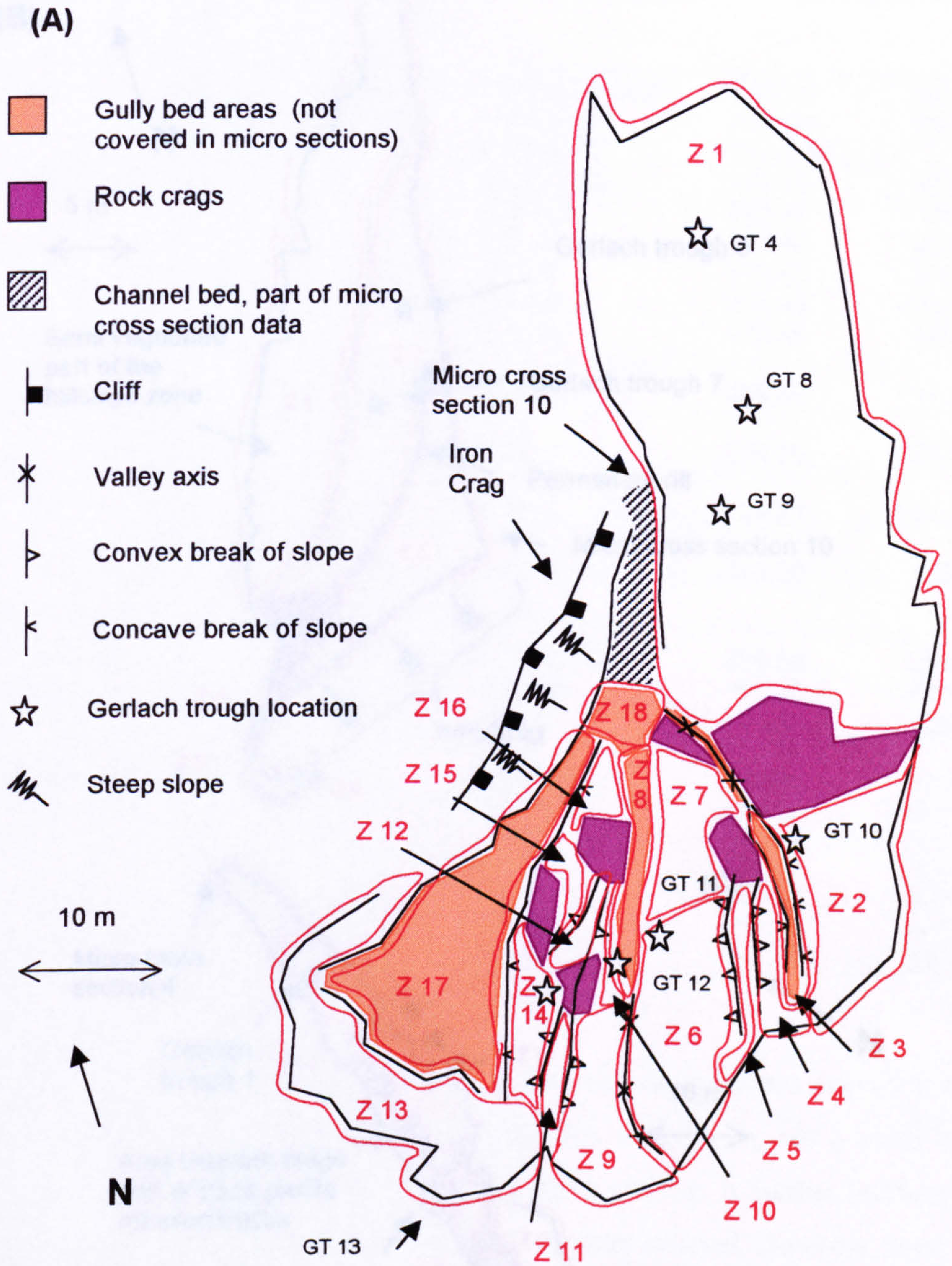
5.2.1.2 Assumptions and limitations in calculating the sediment budget

This section presents the assumptions and limitations of the calculations used in estimating the sediment budget shown in Figures 5.3 and 5.4.

Sediment collected in *Gerlach troughs* is dried in laboratory ovens to obtain the dry mass. The dry mass of sediment from each sampling point, in each measurement interval is the basic information from which wash yields are calculated. The second step is to scale up the collected yields, from a known instrument catchment area to a total source area. Total station survey data are used to construct maps of the primary, sub-primary and secondary hillslope zones. These maps are then divided into simple polygon sub-zones (Figure 5.5). Individual polygons are loaded into SURFER® allowing the slope surface area to be measured. All these measurement grids use linear interpolation between the data points, which is expected to produce an accurate surface given that the survey points were placed strategically to account for breaks of slope in the field. In most cases the choice of grid interpolation procedure had only a small effect on the calculated areas.

Within the primary zone, individual or combinations of polygons were assigned to the Gerlach troughs (Table 5.5). The polygons define different topographic features of the primary zone, namely the individual gully heads and the long right bank slope. The assigned Gerlach trough(s) is the one situated within the polygon group. To scale up the Gerlach trough yield to the polygon area, a calibration factor is multiplied by the measured dry mass (or dry mass sum where two or more Gerlach troughs are used). The calibration factor is the polygon group area (sum of individual polygon areas) divided by the instrument catchment area (see Appendix 5.1: 4). Multiple calibration factors exist where more than one trough is within a polygon group and when a full set of samples could not be obtained during a measurement interval. The primary zone wash yield in a single measurement interval is the sum of all the polygon group yields. In the sub-primary and secondary zones where the topography is less diverse and fewer Gerlach troughs were used a single source polygon is multiplied by an appropriate calibration factor (Table 5.5)

Figure 5.5: Division of hillslopes into simple polygons for surface area measurements. (A) primary zone; (B) sub-primary zone; and (C) secondary zone. (Not the same scale)



Polygon sub-zones (red line perimeter) are shown approximately.

Figure 5.5 cont.:

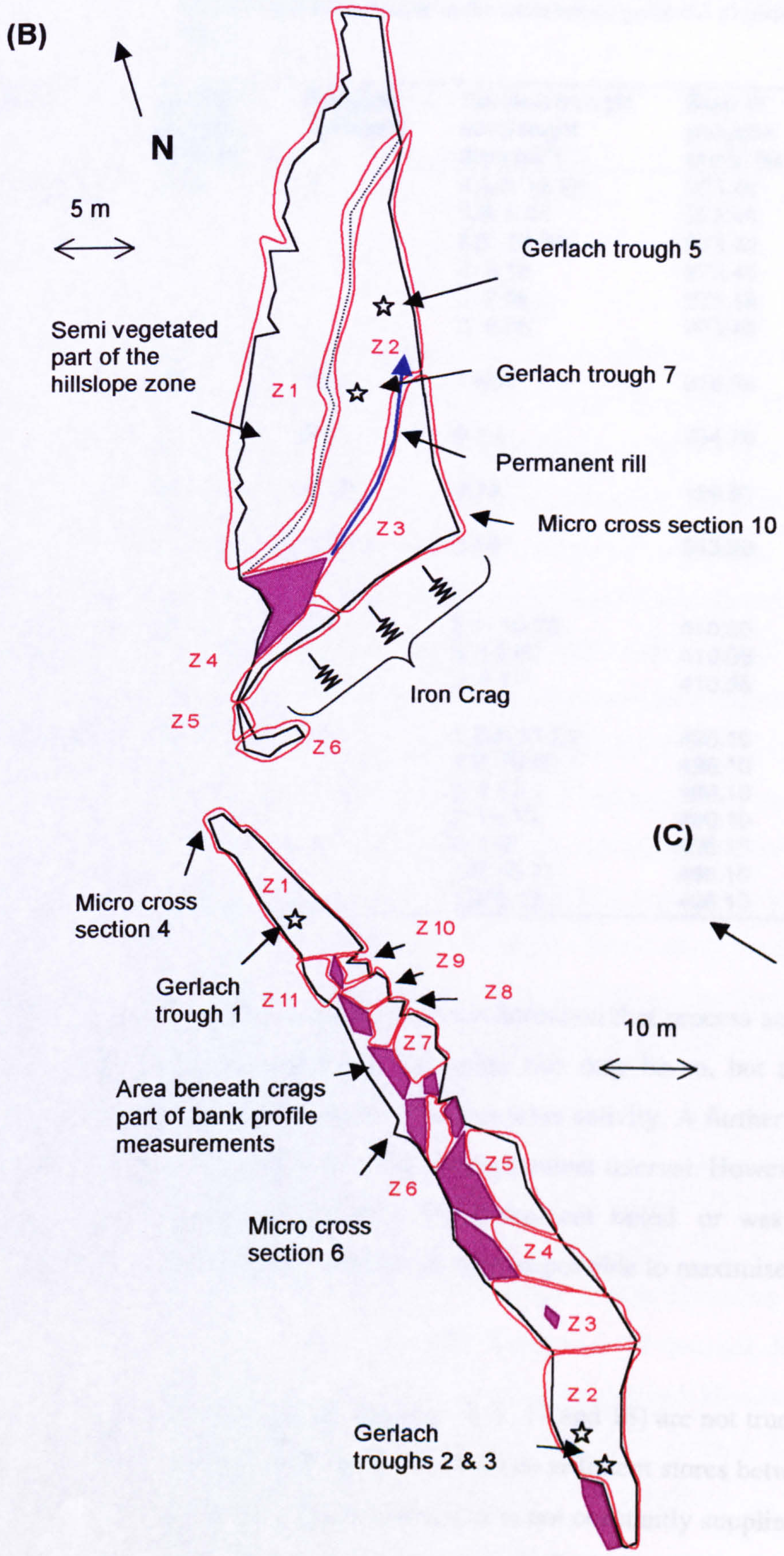


Table 5.5: The allocation of polygon areas to individual Gerlach troughs. The calibration factor multiplied by the Gerlach trough yield provides a scaled up yield. (Several permutations are available in the calculations given the availability of sediment trap data).

Zone	Gerlach trough number	Polygon numbers	Gerlach trough catchment area (m^2)	Sum of polygon areas (m^2)	Calibration factor
Primary	4,8,9	1	4,8,9: 13.92	973.48	69.92
			4,8: 5.84	973.48	166.57
			8,9: 10.74	973.48	90.63
			4: 3.18	973.48	305.88
			8: 2.66	973.48	365.74
			9: 8.08	973.48	120.50
	10	2-5	14.69	219.38	14.94
	11	6-8	9.19	234.70	25.55
	12	9-10	9.74	129.81	13.33
	13	11-18	5.16	543.28	105.37
Sub-primary	5,7	1-6	5,7: 16.78	410.55	24.46
			5: 12.67	410.55	32.39
			7: 4.11	410.55	99.99
Secondary	1,2,3	1-11	1,2,3: 21.23	496.10	23.37
			1,2: 19.62	496.10	25.29
			1: 4.52	496.10	109.78
			2: 15.10	496.10	32.85
			3: 1.61	496.10	307.98
			2,3: 16.71	496.10	29.69
			1,3: 6.13	496.10	80.93

Inherent in this spatial extrapolation is the limitation that process activity is unlikely to be constant across a polygon. In reality this may be so, but a more intrusive monitoring network would interfere with process activity. A further limitation is the variable number of samples from each measurement interval. However, there was no option but to exclude data where the instrument failed, or was not accessible; nevertheless as many trough results are used as possible to maximise the information base.

Some polygons in the primary zone (i.e. 3, 8, 17 and 18) are not true hillslope areas, but more channel like. These gully heads act as sediment stores between parts of the primary hillslope and the channel. Material is not constantly supplied to the channel below, but released in pulses when the gully is flushed out by fluvial activity. Thus the sediment delivery ratio from parts of the hillslope may be zero for much of the time, but then occasionally very large. The issue of sediment delivery is also relevant to the other hillslope zones. The Gerlach trough values provide an indication of the sediment produced, but not the travel distance and thus connectivity of the sediment to the channel. Slope erosion pins were employed to provide a means of estimating spatial variability in sediment delivery; however these data have been rejected due to significant errors (see section 5.2.1.3).

Nets provide information on rockfall activity in the hillslope zones. The nets used are a small selection of the total number available (5 and 6: primary zone; 8 and 9: sub-primary zone; and 14: bedrock step zone), as these are the only nets collecting pure rockfall material. The use of other nets whilst providing a larger sample, would be misleading as sediment is also collected from channel activity and other slope processes. The approach used for scaling the mass of sediment collected in the nets is very similar to that applied with the Gerlach troughs, i.e. scaling yield from instrument area to a total area. However, net instrument areas and total crag areas are determined from scanned images measured using SIGMA SCAN ™ and not from total station survey data. This is because a total station survey would have caused disturbance of the loose crag material and be too dangerous to collect. Scaling factors are determined from objects of known size located in the images. Errors are inherent in this method. In particular photographs fail to show the depth of features. Also problems of depth of field (objects at distance are smaller than same size object in the foreground) enter the measurement. Photographs were taken as close to the crag as possible to minimise these effects.

Furthermore, the spatial scaling of monitored rockfall yields is probably a source of greater error than when applied to Gerlach trough data. This is because rockfall activity and extent is more localised than wash processes. Therefore the scaling up of a small number of monitored net yields (maximum of two net deposits per zone where data available) to the entire area could be questioned. However, in defence of this approach it should be stated that the rockfaces at Iron Crag are heavily weathered and fractured, and rockfall activity is widespread.

Bank profiles establish the amount of material eroded from the banks and supplied to the channel between two measurement surveys. Measurements were made quarterly or after storm events. Despite the potential for unseen activity, these results are the most detailed information available on bank erosion in the system. Comparisons of profile measurements can only be made when the profile markers remain static between measurements. This was not always the case as disturbance by sheep and bank erosion led to some markers being lost. The areas of the bank profile subject to both erosion and deposition are measured. The difference between the sum of all erosion and deposition indicates whether the net behaviour at a particular location is erosional or depositional. A net value has to be used as some of the eroded material may be deposited on the bank and not reach the channel. Where more material is deposited than erodes in a profile, this requires explanation. The most likely source is supply from surrounding bank material. To provide consistency in these measurements several rules were applied. Firstly measurements are confined between the bank top and toe, as defined in the field. Secondly, topples of the bank face which remain attached are excluded, as they imply deposition but in fact are just a relocation of material. Thirdly, failed blocks at the base of banks are still considered to be part of the bank system where they have not been transported away from their original source. Fourthly, where channel material is deposited over a previous bank toe it is not considered bank deposition as the material is not of a bank origin.

The volume of bank material erosion or deposition is the length between two bank profile points multiplied by the mean of the change occurring at the bank profiles. The distance between bank profiles is obtained from total station survey data. Sometimes data for an individual bank profile are not available, due to disturbance of the marker peg, or because the erosion pin was not visible. Where only one profile in a pair exists this is taken to be representative for the entire section. When no profile exists values from the nearest profile on the same bank are used. Having computed the volume of material, it needs to be converted in to mass. This is performed by multiplying the volume by bulk density (1.721 t m^{-3}) (see Table 5.4). The final stage is to calculate the overall mass of bank material eroded on each bankside during the entire period of monitoring.

Micro cross sections measure the amount of erosion or deposition in the channel across a fixed transect. The method used in the calculations shares many common elements with the approach applied to bank profile data. Measurements concentrated on the channel bed and not the entire cross section, as bank material was considered in the previous calculation. Therefore the channel bed is defined as the area between the opposite bank bases or toes. The spatial extrapolation of these results involves three stages, the calculation of the distance between right bank micro cross section markers using total station survey data, the calculation of volumes based on mean net area multiplied by distance, and finally the transfer of volume to mass using the channel material bulk density value of 1.871 t m^{-3}. In the distance calculations the straight line distance between micro sections is used. Where the channel planform is sinuous between micro sections the actual length of channel may be slightly greater than that used in the calculation, leading to an underestimation of the volume of channel material. However, this is only relevant at a few sections because the majority of cross sections were located strategically to encompass slight changes in planform orientation. In the volume calculations where no channel cross section data exist the nearest adjacent section is used. This was only applied to cross section 6, which occasionally lacked results. A substitution with results from section 5 and not section 7 was made, as the latter is very different to section 6.

Fan material changes were measured using a combination of data from the peg array measurements and fan survey areas calculated from total station data. Peg array data are used selectively. Figure 5.6 illustrates and explains which pegs were selected and rejected to measure the fan surface changes. These selections are grouped into three zones that correspond to the fan cone and the right and left bank arms of deposition. For each of these zones the difference in peg height between two measurement intervals indicates whether the surface at that point is erosional or depositional. Further data filtering is used to remove measurements of pegs where no sediment exists, but is instead vegetated. This rule is only applied where vegetation is recorded at both measurements, since the presence of vegetation at one time and not the other can represent the erosion or deposition of sediment, or more rarely the growing of vegetation over the sediment. The exclusion makes the value for change at a given peg zero, which is necessary as any measured differences at this peg would otherwise be represented as sediment erosion or deposition which does not actually occur.

Volumetric change in the fan surface is calculated in each of these sub-zones, i.e. the net volume of sediment deposition or erosion. This is done by creating SURFER® grid files of the fan surface. The X, Y co-ordinates, and an initial Z value are provided by a total station survey of the peg stake locations. Subsequent vertical changes (Z) are measured in the field at reference stakes. SURFER® can then measure the volume of material eroded and deposited between the grid zones. The net volumes for each of the three zones are summed providing a net volumetric measure of change in the fan surface monitored between two measurement intervals. The creation of grid files in SURFER® has been discussed previously, though it is reiterated that the amount of sediment between two pegs is based on a linear interpolation between the two measured values. Therefore a greater density of peg measurements reduces the impact of spatial errors.

As the area of fan deposit was different to the area measured by the peg array it is necessary to perform some spatial scaling of the peg array volumes. An initial requirement is to know the area monitored by the peg array zones, which is easily obtained in SURFER®. Following this the area of the active fan deposit has to be calculated. Surveys of fan deposits were performed with the total station, though only conducted when any perceptible change in the fan deposit area occurred. The first survey was conducted prior to the sediment budget, i.e. 20th September 1998, with successive surveys in March 1999, September 1999, November 1999, and December 1999. Using this survey data the perimeters of sediment deposits are identified, with deposits subdivided into a number of polygons (Figure 5.7). The sum of all polygon areas provides a measure of the total depositional area. The areas of fan deposits, the scaling factor and application of different scaling factors throughout the sediment budget is outlined in Table 5.6. The next stage is to convert these scaled volumes into units of mass. Following previous discussions (section 5.1.2) a bulk density value of 1.871 t m^{-3} is used. Each measurement interval now has a net depositional or erosional mass of sediment. The sum of all erosional and depositional masses provides a quantification of fan activity over the time of monitoring.

Figure 5.6: Fan peg array map, showing the locations of pegs, selected peg array groups (dotted lines) and rejected data (solid lines).

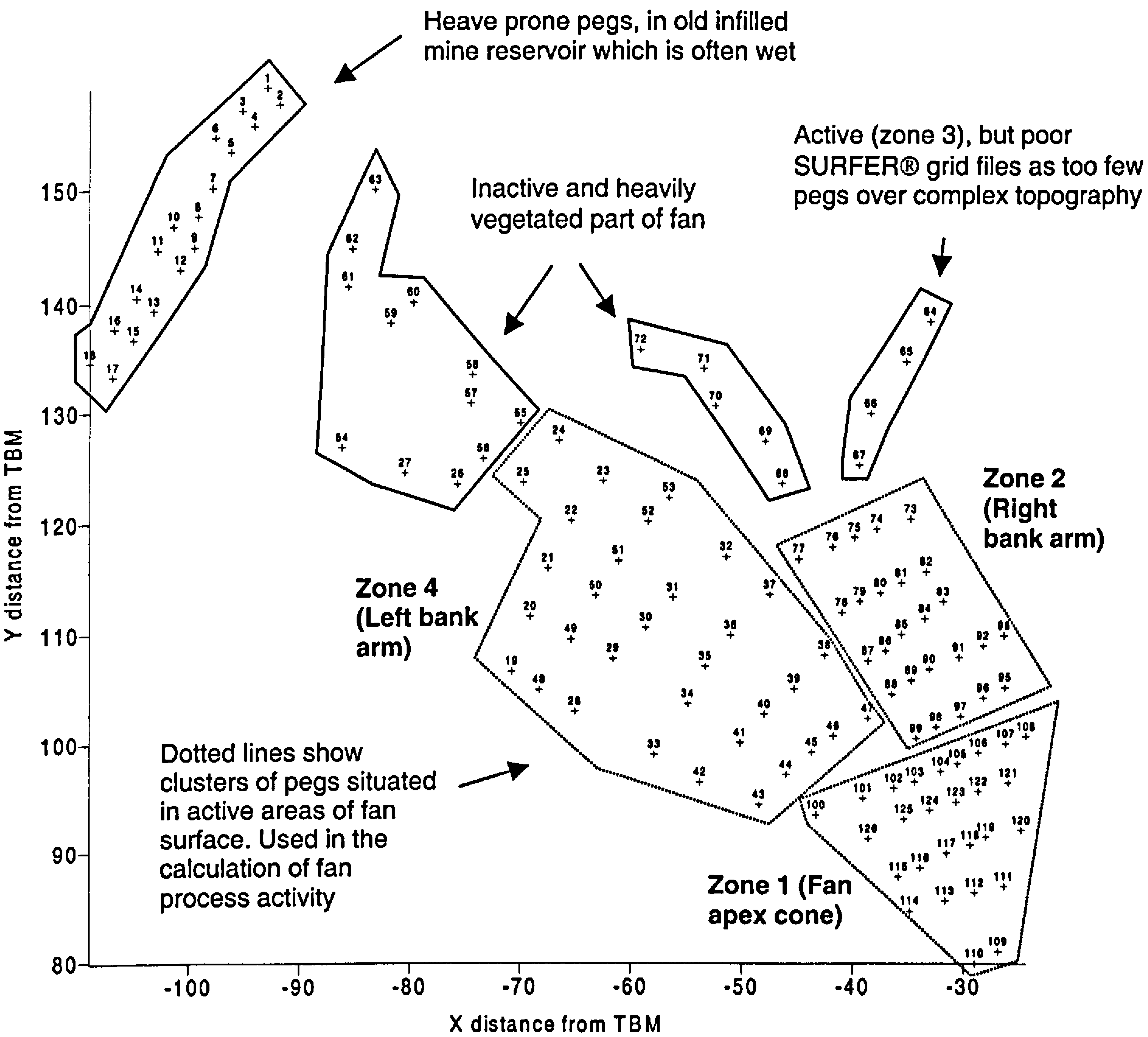
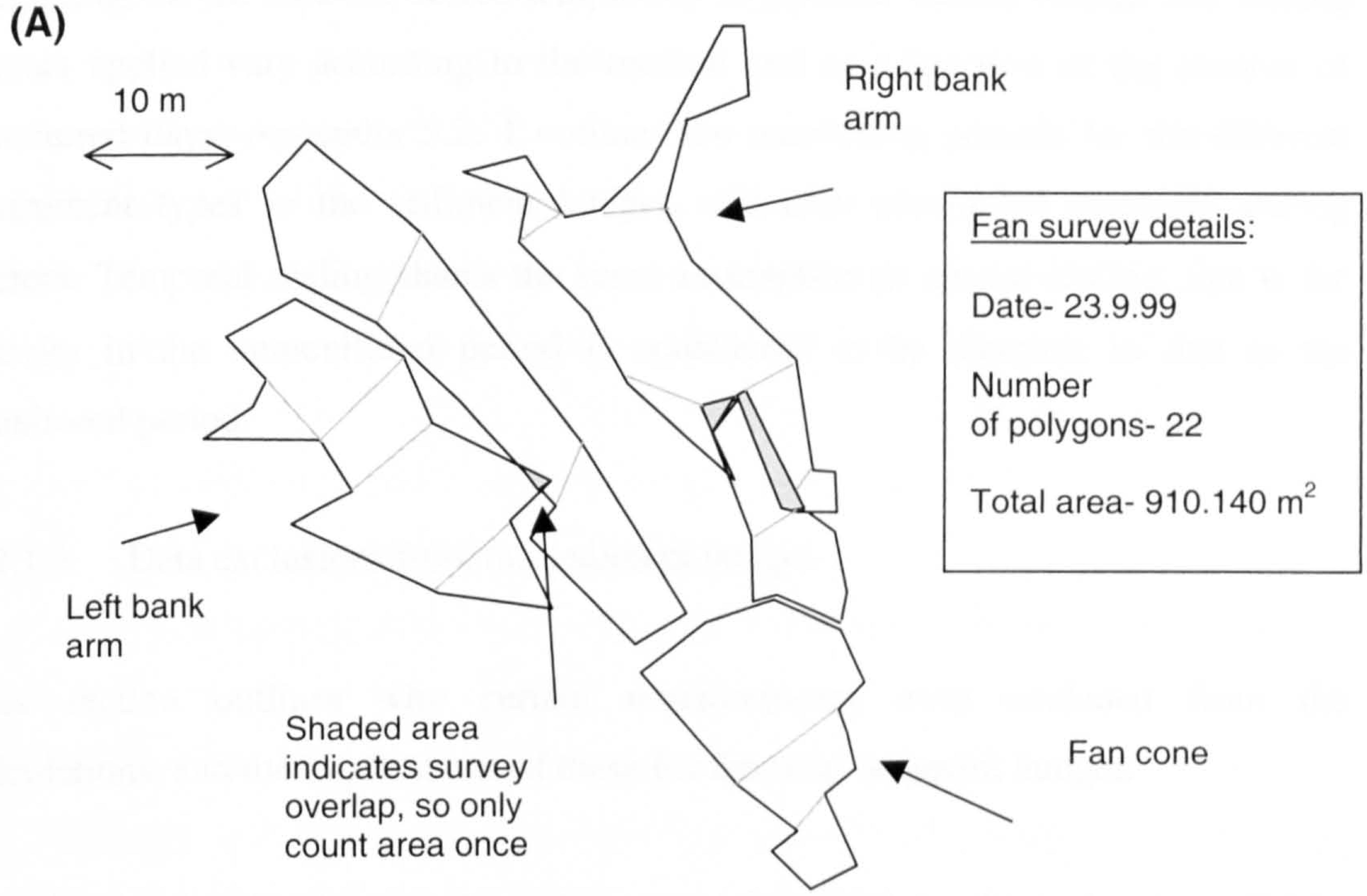
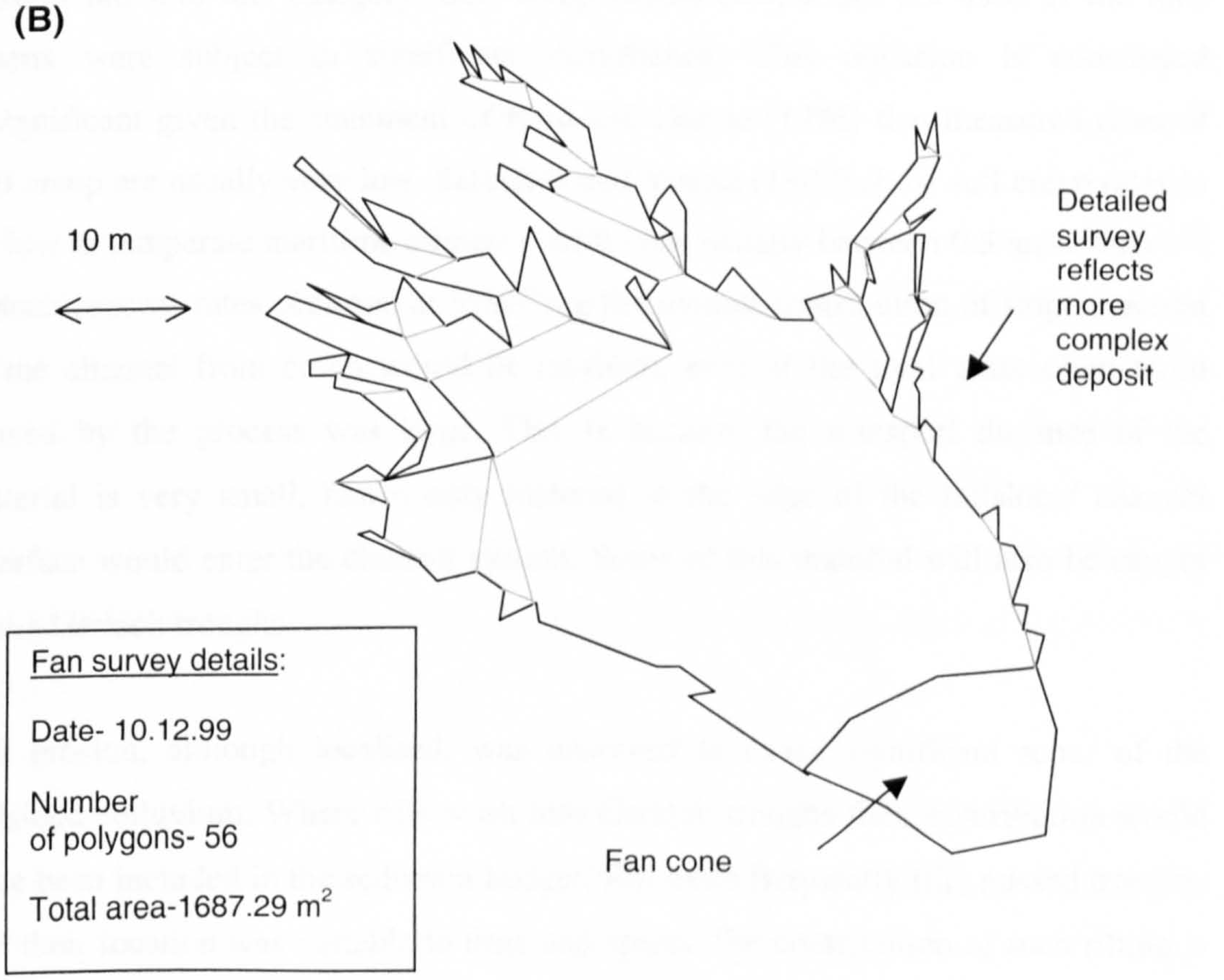


Table 5.6: Spatial scaling of peg array volumes, using scaling factors based on the relationship of peg array area to fan deposit area.

Survey	Fan deposit area (m^2)	Scaling Factor	Application of scaling factor
Pre sediment budget (20.9.98)	777.12	0.8251	Up to 10.3.99
30.3.99	799.32	0.8487	10.3.99 to 2.9.99
23.9.99	910.14	0.9664	2.9.99 to 27.10.99
10.11.99	1071.90	1.1381	27.10.99 to 11.11.99
10.12.99	1687.29	1.7916	11.11.99 to 6.12.99

Figure 5.7: The measurement of fan deposit areas. Two example SURFER ® maps shown for (A) measurement interval 18 (September, 1999); (B) measurement interval 22 (December, 1999). (Not the same scale)





This section has provided a detailed outline of the approaches used in the construction of the sediment budget. Following the basic calculations and spatial weighting, all the data are scaled temporally to produce annual values. The scaling factors applied vary according to the method and as a function of the number of monitored days. Appendix 5.2: 1 outlines the monitoring periods for the different instrument types in the sediment budget, and their associated temporal scaling factors. Temporal scaling shares the same assumption as spatial scaling, that is the activity in the unmonitored period is considered to be identical to that in the monitored period.

5.2.1.3 Data exclusions from the sediment budget

This section outlines why certain measurements were excluded from the calculations, and the implications of these for the final sediment budget.

The first implication is that where data are omitted and no alternative is available, there is a loss of valuable process information from the budget. Soil creep and rill erosion fall into this category. Soil creep measurements are not used as the tube inserts were subject to significant disturbance. This omission is considered insignificant given the statement of Reid and Dunne (1996) that measured rates of soil creep are usually very low. Saunders and Young (1983) show soil creep rates to be low in temperate maritime climates, with rates usually between 0.5 and 2 mm a^{-1}. If such process rates occurred at Iron Crag the overall contribution of slope material to the channel from creep would be minimal, even if the total mass of material moved by the process was large. This is because the transport distance of the material is very small, hence only material at the edge of the hillslope/ channel interface would enter the channel system. Some of this material will also be caught in the Gerlach troughs.

Rill erosion, although localised, was observed to cause significant scour of the hillslope colluvium. Where rills wash into Gerlach troughs their contribution would have been included in the sediment budget. But more frequently rills missed troughs, and their location was variable in time and space. The contribution of such rilling is excluded from the sediment budget. A measurement strategy to quantify the sediment loss from hillslopes to channels due to rilling would have to measure the volume of sediment eroded from the hillslope and the proportion of this which was redeposited on-slope before reaching the channel. The transient nature of most rilling makes instrumentation of rilling very difficult. Only when rills are more permanent features could measurement of erosion be attempted. This was the case at Iron Crag in the sub-primary zone, but attempts to trap eroded sediment failed. Further to this, the rill geometry measurements were subject to disturbance and affected by rill avulsion and sedimentation caused by the draining Gerlach trough. The implication is an underestimation of hillslope sediment delivery to the channel. However, observations indicate that such action is very localised both spatially and temporally.

A second implication of data exclusion is that of no impact on the sediment budget because the process activity is already incorporated in other measurements, or the data is irrelevant to the annual budget. For example the rockfall inventory provides the frequency and timing of fresh rockface areas in the primary, sub-primary, secondary and bedrock step zones. This was performed by comparing 14 base photographs to their respective rock faces in the field, and recording changes on acetate overlays (see Appendix 5.1). Comparing two successive overlays allows the frequency of fresh failures to be counted. Division of this frequency by the number of days between observations allows comparisons to be made (Table 5.7). Overall Table 5.7 shows the frequency of fresh scars to peak through spring, decline through the summer and increase in the autumn, with a final decline in winter. Within this general trend the primary and secondary zones, and the bedrock step and sub primary behave similarly between April and September, but thereafter more local variation is apparent. However, rockfall delivery rates are better determined from the sediment collected in nets, which have a far more precise temporal resolution and measure volume of process activity rather than the frequency of fresh scars. Therefore the rockfall inventory whilst useful is not essential to the construction of the sediment budget.

The channel bank erosion contribution is obtained using bank profiles, rather than the bank erosion pins and planform measurements. Profiles, although measured less frequently, are a better indicator as they consider the entire bank and not just a single

Table 5.7: The frequency of rockfall activity recorded by the rockfall inventory

Measurement Interval	Number days	Zone	Frequency Fresh	Repeat	Fresh frequency d^{-1}
25.11.98- 29.4.99	156	Primary	15	na	0.096
		Sub primary	1	na	0.006
		Secondary	21	na	0.135
		Bedrock step	9	na	0.058
		All	46	na	0.295
29.4.99-16.6.99	48	Primary	8	1	0.167
		Sub primary	0	0	0.000
		Secondary	10	5	0.208
		Bedrock step	2	4	0.042
		All	20	-	0.417
16.6.99- 22.9.99	98	Primary	11	1	0.112
		Sub primary	3	0	0.031
		Secondary	11	7	0.112
		Bedrock step	5	5	0.051
		All	30	-	0.306
22.9.99-17.11.99	56	Primary	4	5	0.071
		Sub primary	0	2	0.000
		Secondary	11	10	0.196
		Bedrock step	7	3	0.125
		All	22	-	0.393
17.11.99-6.1.00	50	Primary	3	3	0.060
		Sub primary	3	1	0.060
		Secondary	5	6	0.100
		Bedrock step	4	3	0.080
		All	15	-	0.300

point upon it. Also bank erosion pins are intrusive, and as a result are subject to disturbance. In the confines of the torrent planform change is incorporated in the bank profile measurements, as these measure the retreat of the bankline. Where local planform changes are significant, then the supply of bank material from planform change may not be fully accounted for.

Channel bed change is obtained from micro section data, which are detailed and surveyed regularly. Figure 5.8 shows a 'macro' cross section illustrating the difference in slope and channel morphology between 28th June 1998 and 17th September 1998. The greatest change occurs in the channel, this finding provides good justification for performing detailed measurements of the channel (i.e. micro cross sections) rather than performing the less detailed macro cross section measurements of both the slope and channel components (see Appendix 5.1: 11, 12). Scour chains as an alternative instrument to measure channel bed changes failed to operate successfully, largely because burial depths were too shallow. Bedload tracers are viewed as an ancillary measurement, showing bedload transport. By the same token the bedload timing logger data is used for other purposes.

The third category, unacceptable errors in measurement accuracy is relevant to slope erosion pin data. Slope erosion pins were designed to provide a measure of the net change in the slope surface, providing comparison with Gerlach trough yields. Using both, it was intended to calculate spatially and temporally specific sediment delivery ratios (SDR) for the transfer of hillslope material to the channel zone. The rejection of slope erosion pin data due to significant errors prevented this. A detailed description and discussion of this exclusion is given below, as it is the most significant exclusion from the sediment budget.

Slope erosion pins were placed in the primary, sub primary and secondary hillslope zones. The volumetric change in the slope erosion pin arrays, once converted into mass using bulk density values specific to each hillslope zone, are compared to a comparable spatial area of Gerlach trough data. The calculation of slope erosion pin results began with the selection of pins in higher-density clusters, in topographically distinct areas. These selections define polygons, and using the same procedure as applied to the fan peg array, grid surfaces can be calculated. Overlaying these grid surfaces allows the calculation of the gross and net volumetric changes in the polygon areas. Both net erosion and deposition are calculated. For net deposition to occur a source is required for the material. As most polygon groups adjoin the top edge of hillslope sources, the material cannot be supplied from upslope, it can only be material from in-between the pins which is eroded and deposited at the pins.

A test was conducted to assess the accuracy of the slope erosion pin results. A SDR of one would suggest identical yields from pin and trough data. If however, the SDR were less than one, then the loss from the slope (Gerlach trough yield) would have to be less than the sediment production (slope erosion pin yield). In this test net erosional data from individual polygons are scaled to appropriate Gerlach trough yield areas. Slope erosion pins suggest far greater sediment losses from the hillslope than shown by the Gerlach troughs, therefore if the slope erosion pin results were accepted they would significantly outbalance the rest of the budget.

Figure 5.8: Macro cross section 5 indicating the different amounts and rates of net erosion associated with channel and slope components

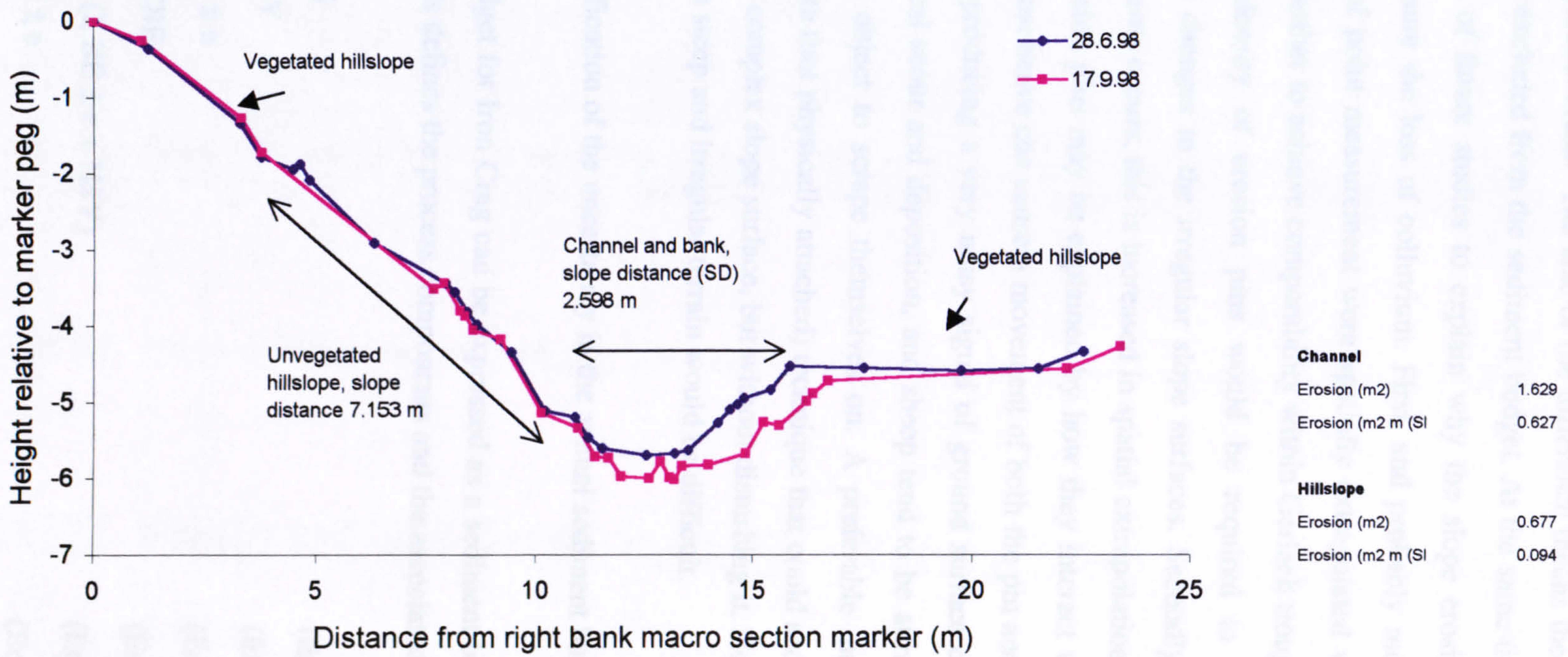


Table 5.8 shows the computed differences in slope erosion pin and Gerlach trough yields for comparable areas. The size of the difference means the slope erosion pin results must be excluded from the sediment budget. At the same time it is important for the benefit of future studies to explain why the slope erosion pins failed to accurately measure the loss of colluvium. First, and probably most importantly, a small number of point measurement were spatially extrapolated within a polygon, and then even further to achieve comparability within Gerlach trough areas. Hence a much greater density of erosion pins would be required to more accurately characterise the changes in the irregular slope surfaces. Secondly, if any error in point measurements occurs, this is increased in spatial extrapolation. Causes of error in the slope erosion pins may be explained by how they interact with the physical environment. Frost heave can cause a movement of both the pin and ground relative to one another, producing a very noisy signal of ground surface change. The pins also promote local scour and deposition, and sheep tend to be attracted to them as they provide an object to scrape themselves on. A preferable monitoring design would be a remote (not physically attached) technique that could accurately measure changes over the complex slope surface, but without disturbing it. However finding a suitable station in steep and irregular terrain would be difficult.

5.2.1.4 Quantification of the uncertainty in the annual sediment budget

The sediment budget for Iron Crag can be expressed as a sediment balance equation (equation 5.1), this defines the process components and the associated error terms:

$$FS_c = TSY - LOSS \qquad \text{(Equation 5.1)}$$

$$TSY = HSY + CSY \qquad \text{(Equation 5.2)}$$

$$HSY = R \pm e + W \pm e \qquad \text{(Equation 5.3)}$$

$$CSY = BE \pm e + CBE \qquad \text{(Equation 5.4)}$$

$$CBE = MXS \pm e - (\Sigma\, BE \pm e + HSY) \qquad \text{(Equation 5.5)}$$

$$FS_m = FA \pm e - FD \pm e \qquad \text{(Equation 5.6)}$$

Equation 5.1 states that the storage of material on the fan surface (FS_c) is the sum of the input (TSY) minus the loss of material from the fan (LOSS). Where 'TSY' is the

Table 5.8: Differences in the calculated yield (mass) between scaled slope erosion pin polygons and Gerlach troughs. (SEP- Slope erosion pin; GT- Gerlach Trough) (SEP zones 1-6-primary; SEP 7- sub-primary; SEP 9- secondary).

SEP zone	GT zones	Monitoring interval	GT yield (kg)	SEP yield (kg)	GT as % of SEP
1	1	5-7	51	6315	0.8
		9-10	14	847	1.6
		13-14	17	3502	0.5
		15-16	14	7223	0.2
		17-18	3	1144	0.3
		18-19	2	4187	0.0
		20-21	6	830	0.8
		21-22	28	3695	0.8
2	2-5	5-7	18	7040	0.3
		9-10	8	159	4.8
		13-14	10	742	1.3
		14-15	1	3283	0.0
		16-17	2	2950	0.1
		17-18	6	513	1.1
		18-19	3	397	0.7
		19-20	1	148	0.8
		20.21	7	600	1.1
4	6-8	5-7	32	1220	2.6
		7-9	8	4821	0.2
		11-12	32	665	4.8
		13-14	70	493	14.3
		14-15	3	739	0.5
		15-16	2	1914	0.1
		17-18	1	177	0.4
		20-21	0.2	77	0.3
5	9-10	5-7	62	2119	2.9
		7-9	40	5210	0.8
		13-14	39	1045	3.7
		14-15	3	5262	0.1
		15-16	40	401	9.9
		17-18	31	113	27.0
		19-20	4	1917	0.2
6	11-18	5-7	469	2262	20.7
		9-10	184	2498	7.4
		10-11	267	6448	4.1
		11-12	20	207	9.4
		13-14	313	28946	1.1
		15-16	282	1818	15.5
		17-18	74	5752	1.3
		18-19	13	1999	0.6
		20-21	35	380	9.1
7	ALL	5-7	19	5234	0.4
		10-11	47	572	8.3
		11-12	42	744	5.7
		12-13	51	373	13.6
		13-14	18	2653	0.7
		14-15	5	584	0.9
		15-16	20	1863	1.1
		17-18	23	1103	2.1
		20-21	8	684	1.2
9	ALL	10-11	131	2802	4.7
		13-14	33	3068	1.1
		14-15	33	1369	2.4
		15-16	29	795	3.7
		16-17	15	114	13.1
		17-18	21	3743	0.6
		18-19	45	8094	0.6
		20-21	27	1400	1.9
		21-22	193	496	38.9

total sediment yield, and is itself composed of the sum of hillslope sediment yield (HSY) and the channel sediment yield (CSY) (Equation 5.2). In Equation 5.3 'R' signifies rockfall, and 'W' the wash component. Whereas in Equation 5.4 'BE' is bank erosion, and 'CBE' is channel bed erosion. As sediment from hillslopes and the banks enter the channel, the micro cross section measurements of the channel dynamics incorporate sediment from these sources. Therefore to calculate the true channel bed contribution the total channel change (MXS) is minus the sum of bank and hillslope contributions (Equation 5.5). The 'e' is the error term associated with the measured component. Importantly, the actual storage of material on the fan surface (FS_m) can also be calculated by the subtraction of measured fan accretion (FA) from the measured fan degradation (FD) (Equation 5.6). Hence, the fact that all components are measured avoids the need to calculate residual terms, which Kondolf and Matthews (1991) states to be deceptive, as they are the sum of all errors in measured components. Despite the advantage of having a fully monitored, virtually closed system the issue of quantifying the errors within the measured components remain. Kondolf and Matthews (1991) point out that in cases like that of the Iron Crag sediment budget, where all terms are measured, the need to calculate errors arises from the net imbalance between inputs (TSY) and outputs (FA or FS_m). These imbalances are cited to be greatest when processes are infrequent, the study period short or where low sediment yields are involved.

To quantify errors they first must be identified. Table 5.9 outlines the errors associated with each component. This draws on the discussions in section 5.2.1.2, and also further sources of error are identified here. From this the main types of error in the sediment budget are summarised:

1. Error in the initial measurement, i.e. catch efficiency, reading measurements.
2. Error due to converting volumes to mass, i.e. errors associated with measurements of bulk density.
3. Error associated with the spatial efficiency of the instruments, i.e. location and number of instruments, and also the validity of subsequent spatial extrapolation.
4. Errors in calculating surface areas.
5. Errors of temporal extrapolation.

Of these main error types only some are quantifiable, the remainder are assumed to be having a small effect in the overall sediment budget. Table 5.10 identifies these errors. Errors calculated are cumulative, indicating the maximum probable error in component yields (excluding scaling error), expressed as a percentage.

Measurement errors in bank and channel surveys were determined by performing repeat measurements (3 surveys per location) of a number of bank profile and micro cross sections. As no process activity had occurred between intervening measurements all the measurements should be identical, and any deviation is therefore considered a measurement error. Differences between two survey profiles are both positive repeat survey line above initial) and negative (repeat survey below initial line). The sum of all positive and negative changes between profiles gives a net deviation measured as an area (cm^2), an average area is then obtained from the three profile comparisons at each location. The mean error is then divided by actual areal changes at the same locations, obtained in the sediment budget calculations at each measurement interval, and expressed as a percentage. Where the percentage value is greater than 100 % the areal error is larger than the measured change in a bank face or channel bed, suggesting the observed change could be a function of measurement rather than process activity. This is particularly rare, in the majority of cases the measurement error area is considerably less than the measured change (see Appendix 5.2: 2, 3). Finally, the median of these percentages gives the overall percentage error as a function of measurement. The median is superior to a mean value as the latter is biased to extreme values in the data set. For channel bed erosion the median measurement error is 9.1 %, and 18.6 % for bank profiles.

Bulk density errors are the main remaining errors. As multiple samples were used to calculate the mean bulk density values of channel and bank material, standard deviations allow errors to be calculated, by expressing the standard deviation as a percentage of the mean value. The channel bulk density value of 1.871 t m^{-3} has a standard deviation of 0.217 or 11.6 %, whereas the bank bulk density of 1.721 t m^{-3} has a standard deviation of 0.218 or 12.7 %. Adding these values to the respective measurement errors (given above) gives estimates of the maximum probable errors: channel (20.7 %), bank (31.3 %).

Errors in the fan peg array measurements were calculated from a repeat survey (3 measurements of each peg) of 10 pegs situated in fan gravels. The smallest exposure length is expressed as a percentage of the longest exposure (range 1-8 %). The mean of these ten measurements is 4.7 %. As with the channel and bank measurements a bulk density percentage is added to achieve a maximum probable error percentage, which is 11.6 % following the use of the channel bulk density value for the fan sediments, hence the sum of errors is 16.3 %.

Adjusting the annual component yields presented in Figure 5.3 using the error percentages specified, it is possible to calculate maximum probable errors for each component yield. Of the four input components (CBE, BE, R, W) the first two have two new possible values, i.e. calculated yield plus error (t + e%) percentage, and calculated yield minus error percentage (t – e%). Whereas the rockfall (R) and wash components (W) are assumed to be correct and therefore have a 0 % error for the purposes of this analysis. The number of possible combinations is the square of the number of variable input components, i.e. $2^2 = 4$ (assuming that the variable input values are never considered to have a 0% error). Comparing the combinations of input yields (TSY) with the fan accretion (FA) allows the issue of imbalance (Figure 5.3) between the two to be investigated. In this comparison (Table 5.11) three values of FA are used, i.e. the calculated value, and maximum probable error values. Table 5.11 shows that the input yield, i.e. supply of material to the fan has a minimum value of 142.47 t, and a corresponding maximum of 224.81 t, a range of ± 41.2 tonnes of the original (best estimate) yield value (183.64 t).

Table 5.9: Sources of error in the calculation of the sediment budget components

Stage of calculation	Source of error	Relevant component Instrument/ survey	Comments
Field	Poor instrument performance	Peg array	Apparent changes due to local scour and fill, and frost heave. Exclude heave prone pegs in the calculations.
	Spatial density of instruments	Peg array, Micro cross sections, Bank profiles, Gerlach troughs, Nets	Where measurements are not intrusive a greater number would increase data without effect. But larger numbers of traps would alter the movement of sediment across the hillslope.
	Catch efficiency of instruments	Gerlach troughs, Nets	Troughs well adapted for granular particle size. But overflow of instrument is a loss of data- rarely occurs. Nets have the problems of filtering finer fragments and fragment bounce out on impact, therefore a loss of yield. Rockfall deposits coarser so less filtration loss, known by observation of input and loss.
	Measurement accuracy	Peg array, Micro cross sections, Bank profiles	Accuracy (difference relative to actual) is variable (see Appendix 5.2). Vertical measurements less accurate than horizontal.
Post- field	Surface area measurements	Peg array, Micro cross sections, Bank profiles, Gerlach troughs, Nets	Use simple grid files in SURFER®, small number of survey points limits the accuracy of the result. Crag areas for Nets use measurements from photographs that are subject to perspective problems.
	Volume to mass conversion	Peg array, Micro cross sections, Bank profiles	Very sensitive to the density value used. The mean value used fail to fully consider spatial and temporal variability.
	Surrogate measurements	Micro cross sections, Bank profiles, Gerlach troughs, Nets	Where measurements unavailable other local values used. Required to achieve complete calculations. Assumes uniformity.
	Spatial extrapolation	Peg array, Micro cross sections, Bank profiles, Gerlach troughs, Nets	Means of applying point measurements to a larger area. It assumes these are accurate, and if not introduces bias. It further assumes uniformity throughout the area.
	Temporal extrapolation	Peg array, Micro cross sections, Bank profiles, Gerlach troughs, Nets	Required to achieve sediment yields over 365 days. Scaling usually very small, though up to 9.5% of a year. Assumes unmeasured identical to measured.

Table 5.10: The treatment of the main errors in the Iron Crag sediment budget component yield estimates

Component	Error type	Treatment
Rockfall (R)	Sampling efficiency	Considered accurate
	Scaling errors	Assumed accurate
Wash (W)	Sampling efficiency	Considered accurate
	Scaling errors	Assumed accurate
Bank erosion (BE)	Survey error	CALCULATED
	Scaling error	Assumed accurate
	Bulk density conversion	CALCULATED
Channel bed erosion (CBE)	Survey error	CALCULATED
	Scaling error	Assumed accurate
	Bulk density conversion	CALCULATED
Fan accretion (FA) and Fan degradation (FD)	Measurement error	CALCULATED
	Scaling error	Assumed accurate
	Bulk density conversion	CALCULATED

Table 5.11: Error estimation in the Iron Crag sediment budget components

INPUT (TSY)		Input as a percentage of FA		
Sums of input (t)	Input Error combination	% of original FA 193.86 t	16.27 % increased FA 225.40 t	16.27% decreased FA 162.32 t
142.47	2	73.49	63.21	87.77
171.29	4	88.36	75.99	105.53
183.64	**Original**	**94.73**	**81.47**	**113.13**
195.98	3	101.09	86.95	120.74
224.81	1	115.96	99.74	138.50
Maximum value	224.81	115.96	99.74	138.50
Minimum value	142.47	73.49	63.21	87.77
Original value	183.64	94.73	81.47	113.13

Combinations of input
(+ = original plus error margin
and - = original minus error margin)

1	2	3	4
CBE +	CBE -	CBE +	CBE -
R	R	R	R
W	W	W	W
BE +	BE -	BE -	BE +

Comparing the range of possible input values with the best estimate of fan accretion it can be seen that the best estimate of input and error combinations 2 and 4 are less than the fan accretion, whilst error combinations 3 and 1 show the reverse relationship. Further variability in the input- fan accretion relationship exists when the errors in the fan accretion are considered. With an increased fan value (225.40 t), all input values are less, at worst the negative imbalance is 36.79%, and at best 0.26 %. Conversely where the fan accretion value is reduced by 16.3% (162.32 t) all but one of the input values exceed the fan value. The range of imbalance is from 12.23 % less than the fan accretion to 38.50 % in excess of the fan value. It is only under two scenarios that a near balance is achieved in the TSY to FA relationship, i.e. input combination 3 and the original fan accretion (+1.09 % imbalance); and, input combination 1 and increased fan accretion (-0.26% imbalance). Selecting any of these scenario's requires justification: it is better to conclude that errors exist in the sediment budget yields and therefore the values presented in Figure 5.3 are best estimations. These are most indicative of the relative roles of process components and their linkages in the torrent system rather than the precise yields of sediment attributed to each component during the sediment budget monitoring period.

Comparing the range of error margins (Table 5.11) with those of other published sediment budgets as outlined by Kondolf and Matthews (1991) shows similar errors in the Iron Crag sediment budget. The studies of Madej (1982); Swanson *et al.* (1987); Weaver *et al.* (1991); and Nolan (1991) had positive imbalances of between 1 and 104 %, i.e. inputs in excess of output. In contrast to these findings the original Iron Crag sediment budget values show a negative imbalance of 5.27%. The important point is the magnitude of the imbalances rather than their direction. Iron Crag's range of imbalance, i.e. –36.79% to + 38.50% is not too dissimilar to the imbalances reported by Swanson *et al.* (1987); Weaver *et al.* (1991), + 20% and + 10 % respectively. Not too much should be drawn from this, as the study area is much larger in the case of Weaver *et al.* (1991), and both these examples were compiled from longer-term monitoring programs involving different processes.

So far no mention has been made of the loss of material from the fan (FD). The original estimate is 46 tonnes. Some material is known to exit the fan into Todd Gill and the distal mine reservoirs. Other losses probably include the loss of material in solution and suspension; and apparent erosion effects due to heave of pegs, the compaction of sediment *in situ* due to trampling, and the lateral spreading of sediment between pegs. To test the importance of suspended sediment losses the magnitude of this component is estimated.

In the absence of a rigorous suspended sediment sampling programme, flow is divided into periods of storm activity and baseflow. The duration of these periods during the year is multiplied by representative values of discharge and suspended sediment concentration allowing an approximation of the suspended sediment yield (Table 5.12). Storm periods follow the definition of rainfall events as used in Chapter 4, i.e. rainfall recorded in two or more consecutive hours. During the annual sediment budget monitoring period 1672 hours of rainfall events occur (19.09% of the year), the remaining proportion is considered to be baseflow (7088 hours, 80.91% of the year). Suspended sediment and channel discharges were sampled periodically throughout the sediment budget period inclusive of two storm events on the 26.11.99 and 6.12.99. These provide the data for the determination of representative values (mean and maximum) (see Appendix 5.2: 4). The various combinations of input values gives a range of suspended sediment yields. Table 5.13 shows the extent to which suspended sediment load could account for the loss of material from the fan surface. Three values of FD are used, i.e. FD original (46.05 t); FD plus maximum probable error (53.54 t); and FD minus maximum probable error (38.56 t). The maximum calculated suspended yield accounts for 37.6 % of the fan loss, the minimum 1.2 %. The most probable yield is the minimum value (S1 B1), as this is based on mean values of both discharge and sediment load during the storm periods, rather than a bias to peak values.

The implications of these calculations of suspended sediment yield are twofold. Firstly, that suspended sediment yield cannot account for the loss of material from the fan surface at Iron Crag. Therefore other explanations including scaling errors and apparent erosion effects must play a role. Secondly, to better establish the role of suspended sediment losses continual monitoring of flow and turbidity will give considerably more accurate results. Both are now being measured at Iron Crag.

Table 5.12: Calculation of suspended sediment yields for the Iron Crag torrent, using characteristic values of flow, sediment concentration; and storm and baseflow duration over the sediment budget monitoring period

Flow type and input label	Discharge ($l\ s^{-1}$)	Suspended sediment concentration ($g\ l^{-1}$)	Time (s)	Suspended sediment Yield (g)	Suspended sediment Yield (t)
Storm (S)					
S1	1.13	0.081	6019200	550937.38	0.55
S2	1.13	0.329	6019200	2237757.98	2.24
S3	7.25	0.081	6019200	3534775.2	3.53
S4	7.25	0.329	6019200	14357296.8	14.36
Baseflow (B)					
B1	0.31	0.012	25516800	94922.5	0.09
B2	0.44	0.012	25516800	134728.7	0.13

Table 5.13: The extent to which suspended sediment yields account for the loss of material from the fan surface (FD), with a range of initial discharge and concentration values. (The input labels are given in Table 5.12, each combination represents a particular storm and baseflow type applied to the sediment budget period).

Input combination (s= storm, b= baseflow)	Calculated suspended sediment yield (t)	% accounts for original FD (46.047 t)	% accounts for FD + error (53.539 t)	% accounts for FD – error (38.555 t)
S1 B1	0.65	1.40	1.21	1.68
S1 B2	0.69	1.49	1.28	1.78
S2 B1	2.33	5.07	4.36	6.05
S2 B2	2.37	5.15	4.43	6.15
S3 B1	3.63	7.88	6.78	9.41
S3 B2	3.67	7.97	6.85	9.52
S4 B1	14.45	31.39	26.99	37.48
S4 B2	14.49	31.47	27.07	37.59

5.2.2 Temporal variability

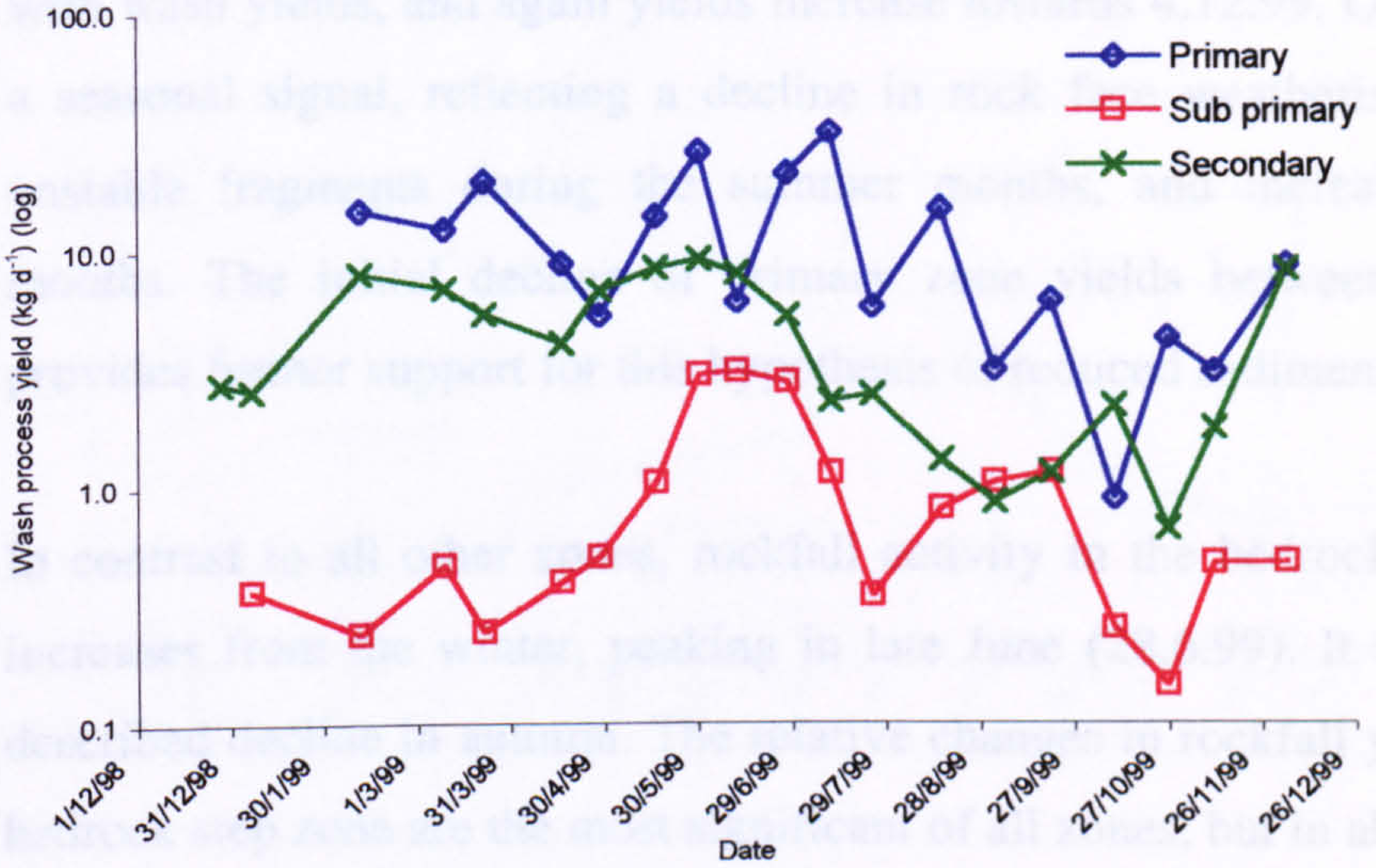
During the monitoring period significant differences in the rates of process activity were observed. The aim here is to interpret these changes using yield data. In the analyses that follow temporal analysis is conducted on zonal results, measured in kg d^{-1}, and categorised by process component. Figures 5.9 to 5.11 show the variability in each component between measurement intervals throughout the monitoring period. It should be noted that the exact dates comprising a measurement interval vary according to the component, as measurements were made on different days. Hence the dates given in the following discussion are component specific.

Figure 5.9 (A) shows wash process rates by zone. The primary zone fluctuates more than the sub-primary and secondary zones, which exhibit smoother and lower yield, especially when it is noted that the Y axis is logarithmic. Also in any given measurement interval the yields vary between the different zones. In contrast to this, longer-term changes show more similarity. First, the primary and secondary zones show higher yields during the winter and spring measurement intervals (28.12.98 to 12.6.99), both of which decline during the summer and into early autumn (12.6.99 to 2.9.99: 10.10.99). Within this general trend subtleties exist, namely the timing of the decline from higher to lower yields. The secondary zone only maintains high yields until 12.6.99 whilst in the Primary zone the peak yield occurs on 12.7.99. Minimum values for both zones are achieved in October 1999, which is rapidly followed by increasing yields in early winter. This cyclicity of sediment supply and relative exhaustion, although exhibiting scatter, would tend to suggest some seasonal control on sediment yields.

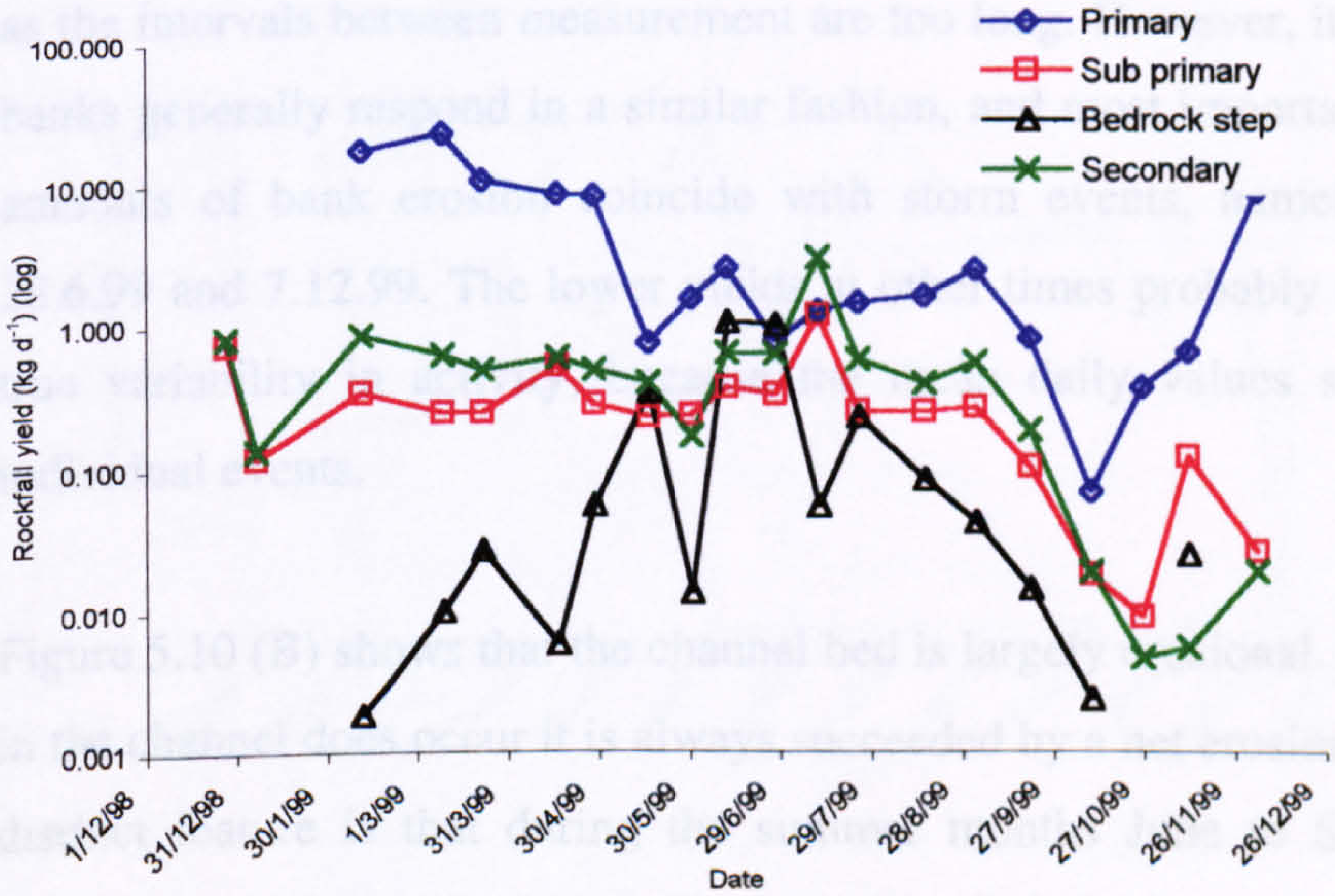
In contrast wash activity in the sub-primary zone shows differences from the patterns described above. Here winter/ spring yields (7.1.99 to 29.4.99) are less than those occurring in the early summer (31.5.99 to 28.6.99). Like other zones there is a summer/ autumn decline in yields (28.6.99 to 10.10.99) and winter resurgence, though less marked than observed in the primary and secondary zones. The overall behaviour of the sub-primary yields may be a reflection of a more localised control, a possible explanation of which may be seasonal changes in sheep numbers. Sheep are removed from the fells to lower pastures during the winter months, but graze

Figure 5.9: **Temporal variability of sediment budget components throughout the monitoring period. (A) Wash processes and (B) Rockfall**

(A)



(B)



the fells in spring and summer. The sub-primary Gerlach troughs may be sensitive to this, as the sheep regularly crossed this zone. The other zones are less accessible.

Figure 5.9 (B) illustrates rockfall yields. The sub-primary and secondary zones show very similar trends. These zones also share some similarity with the primary zone. From 31.5.99 to the end of the monitoring period all zones behave in a broadly similar manner. From 31.5.99 to 2.9.99 rockfall yields are relatively stable, but from 2.9.99 to October 1999 yields decline. This is identical to the low point occurring with wash yields, and again yields increase towards 4.12.99. Once more this may be a seasonal signal, reflecting a decline in rock face weathering and exhaustion of unstable fragments during the summer months, and increased yields in winter months. The initial decline of primary zone yields between 7.1.99 and 29.4.99 provides further support for this hypothesis of reduced sediment production.

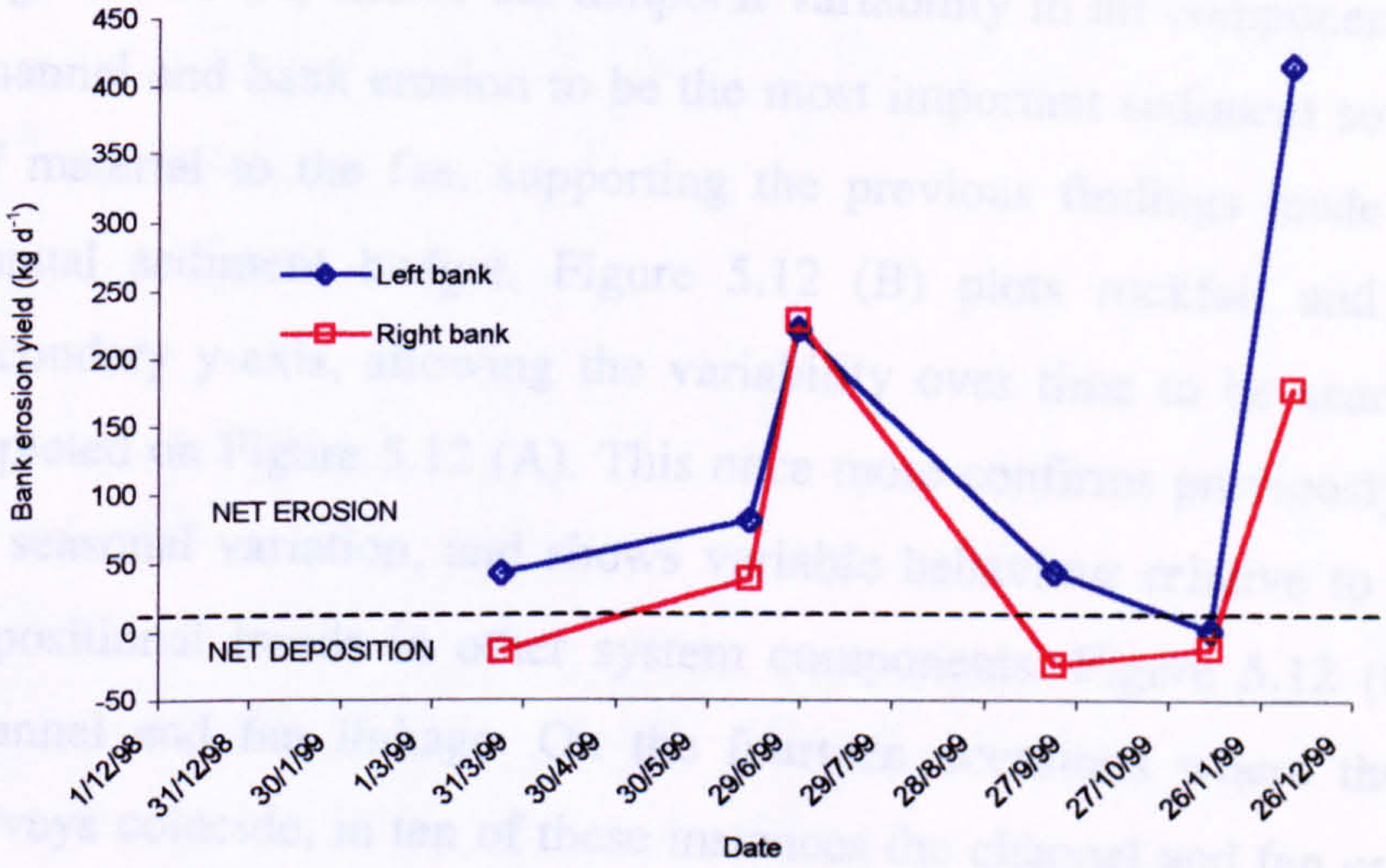
In contrast to all other zones, rockfall activity in the bedrock step zone generally increases from the winter, peaking in late June (28.6.99). It shows the previously described decline in autumn. The relative changes in rockfall yields observed in the bedrock step zone are the most significant of all zones, but in absolute terms they are minor when the logarithmic scale is considered.

Figure 5.10 (A) does not allow seasonal interpretation of process activity to be made, as the intervals between measurement are too long. However, it does show that both banks generally respond in a similar fashion, and most importantly that the greatest amounts of bank erosion coincide with storm events, namely measurements on 28.6.99 and 7.12.99. The lower yields at other times probably disguise some of the true variability in activity, because the mean daily values smooth the effect of individual events.

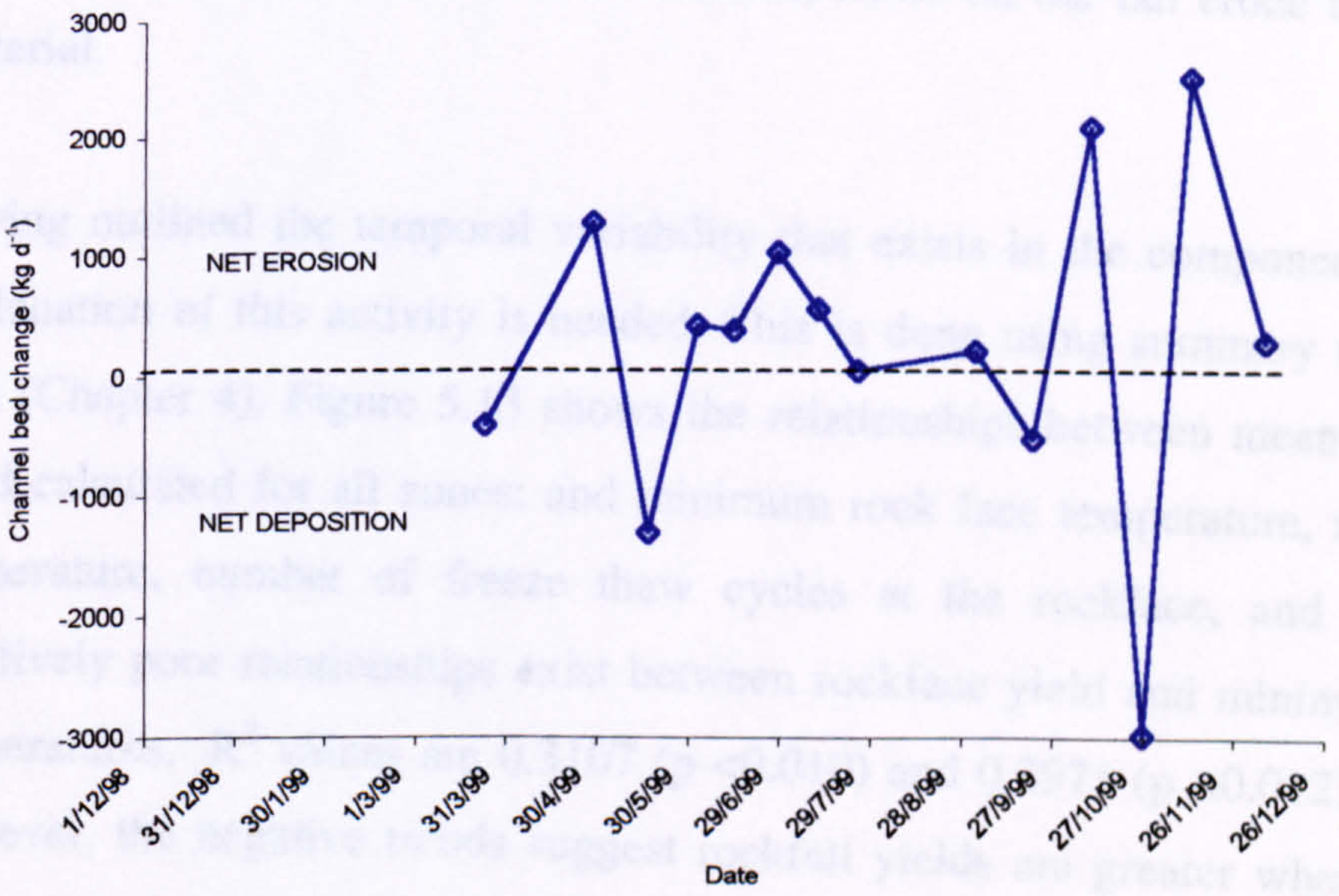
Figure 5.10 (B) shows that the channel bed is largely erosional. When net deposition in the channel does occur it is always succeeded by a net erosional change. The most distinct feature is that during the summer months June to September (2.6.99 to 2.9.99) the channel shows sustained erosion. This is the most consistent behaviour throughout the entire monitoring period. The greatest net daily summer erosion occurs prior to 28.6.99, which was the response to a summer storm. In contrast to

Figure 5.10: **Temporal variability of sediment budget components throughout the monitoring period. (A) Bank erosion yield, and (B) Channel sediment yield**

(A)



(B)



this, there are periods of instability in the winter-spring and autumn-winter phases of the monitoring period, with significant fluctuations between erosion and deposition. Figure 5.11 shows that fan sedimentation fluctuates throughout the year. No seasonal control is apparent, but like bank erosion individual events have a noticeable effect. The storm effects measured on 11.11.99 and 6.12.99 caused significant deposition on the fan surface; input from the channel is required to account for this output.

Figure 5.12 (A) shows the temporal variability in all components and demonstrates channel and bank erosion to be the most important sediment sources for the supply of material to the fan, supporting the previous findings made with regard to the annual sediment budget. Figure 5.12 (B) plots rockfall and wash yields on a secondary y-axis, allowing the variability over time to be seen more clearly than depicted on Figure 5.12 (A). This once more confirms previously established trends of seasonal variation, and shows variable behaviour relative to both erosional and depositional trends in other system components. Figure 5.12 (C) investigates the channel and fan linkage. On the fourteen occasions where the channel and fan surveys coincide, in ten of these instances the channel and fan oppose each other in net behaviour. Thus when the channel is erosional the fan is depositional (n=8), and when the channel is depositional the fan is erosional (n=2). This suggests that when material is being deposited in the channel, flows on the fan erode the existing fan material.

Having outlined the temporal variability that exists in the component data, further explanation of this activity is needed. This is done using summary meteorological data (Chapter 4). Figure 5.13 shows the relationships between mean daily rockfall yield calculated for all zones; and minimum rock face temperature, mean rockface temperature, number of freeze thaw cycles at the rockface, and total rainfall. Relatively poor relationships exist between rockface yield and minimum and mean temperatures, R^2 values are 0.3107 ($p < 0.010$) and 0.2971 ($p < 0.012$) respectively. However, the negative trends suggest rockfall yields are greater when it is colder. More convincing is the relationship between rockfall and the number of freeze-thaw cycles. As the number of freeze-thaw cycles in a measurement interval increase, so too does the rockfall yield, with a R^2 of 0.7792 ($p < 0.0000002$). Following the finding of Matsuoka (1990) that rainfall may be a further means of explaining

Figure 5.11: **Temporal variability of mean daily fan surface change throughout the sediment budget monitoring period.**

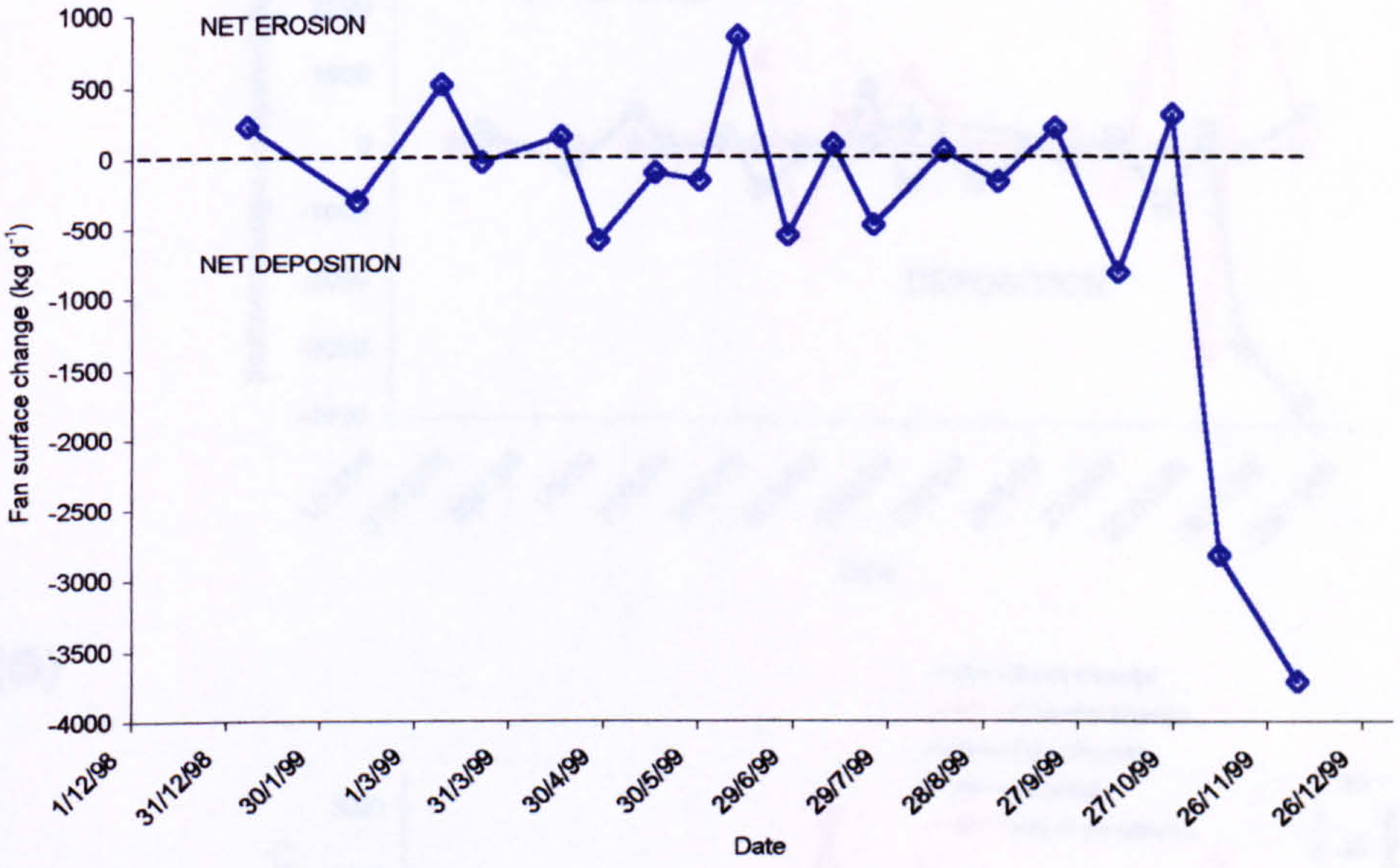
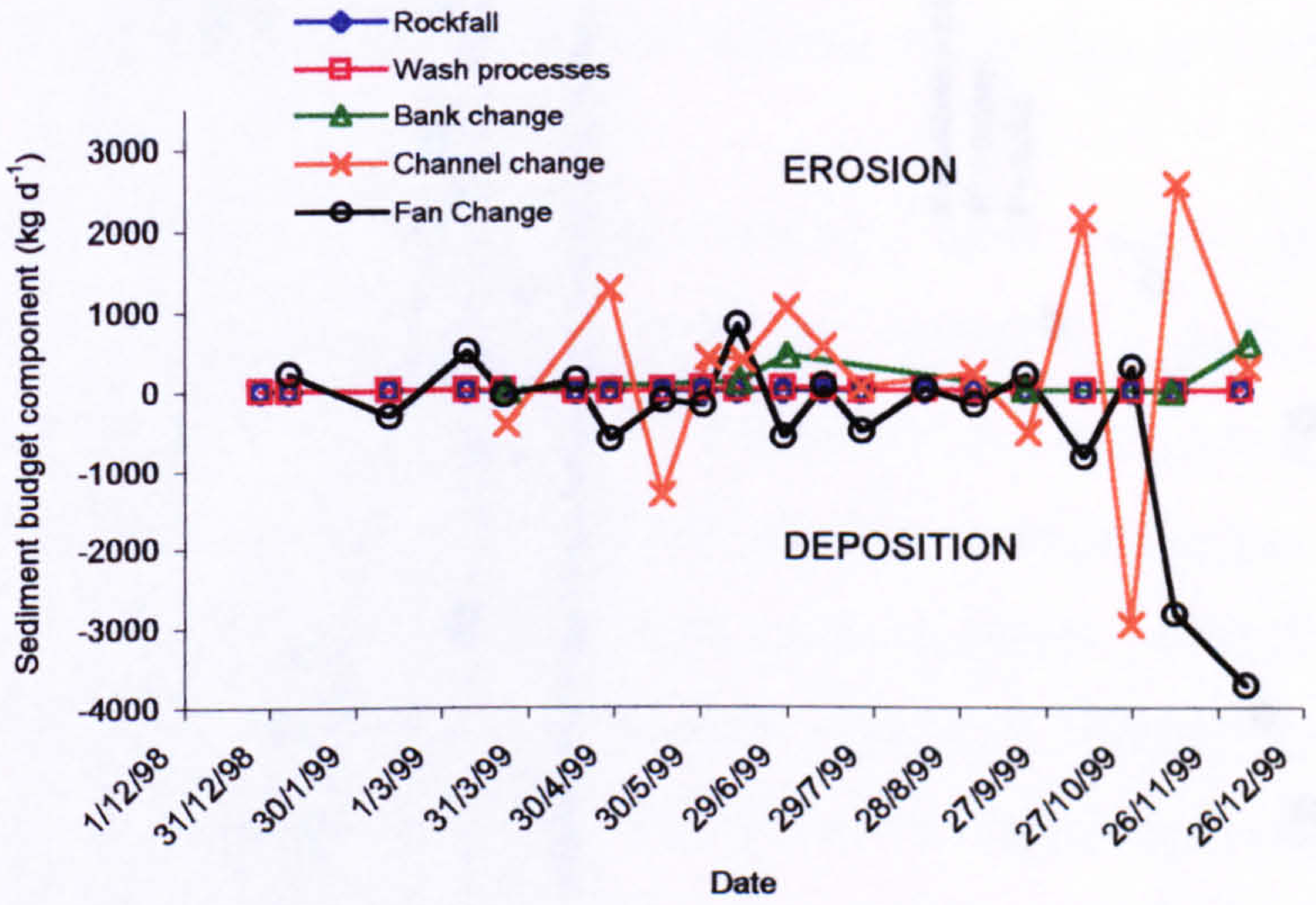
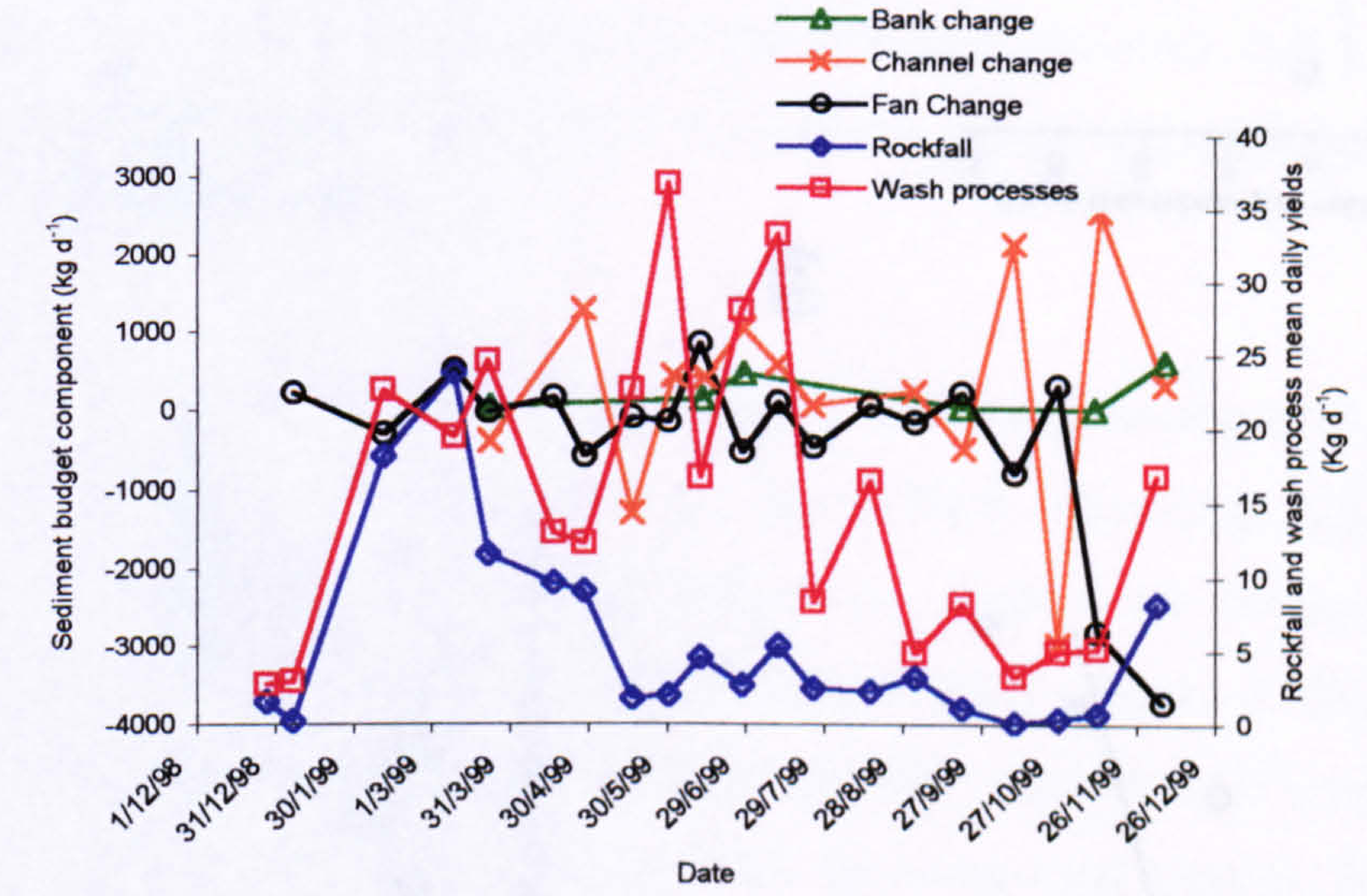


Figure 5.12: Temporal variability in sediment budget components. (A) All components, (B) All components with separation of rockfall andwash processes, (C) Relationship between channel and fan process activity

(A)



(B)



(C)

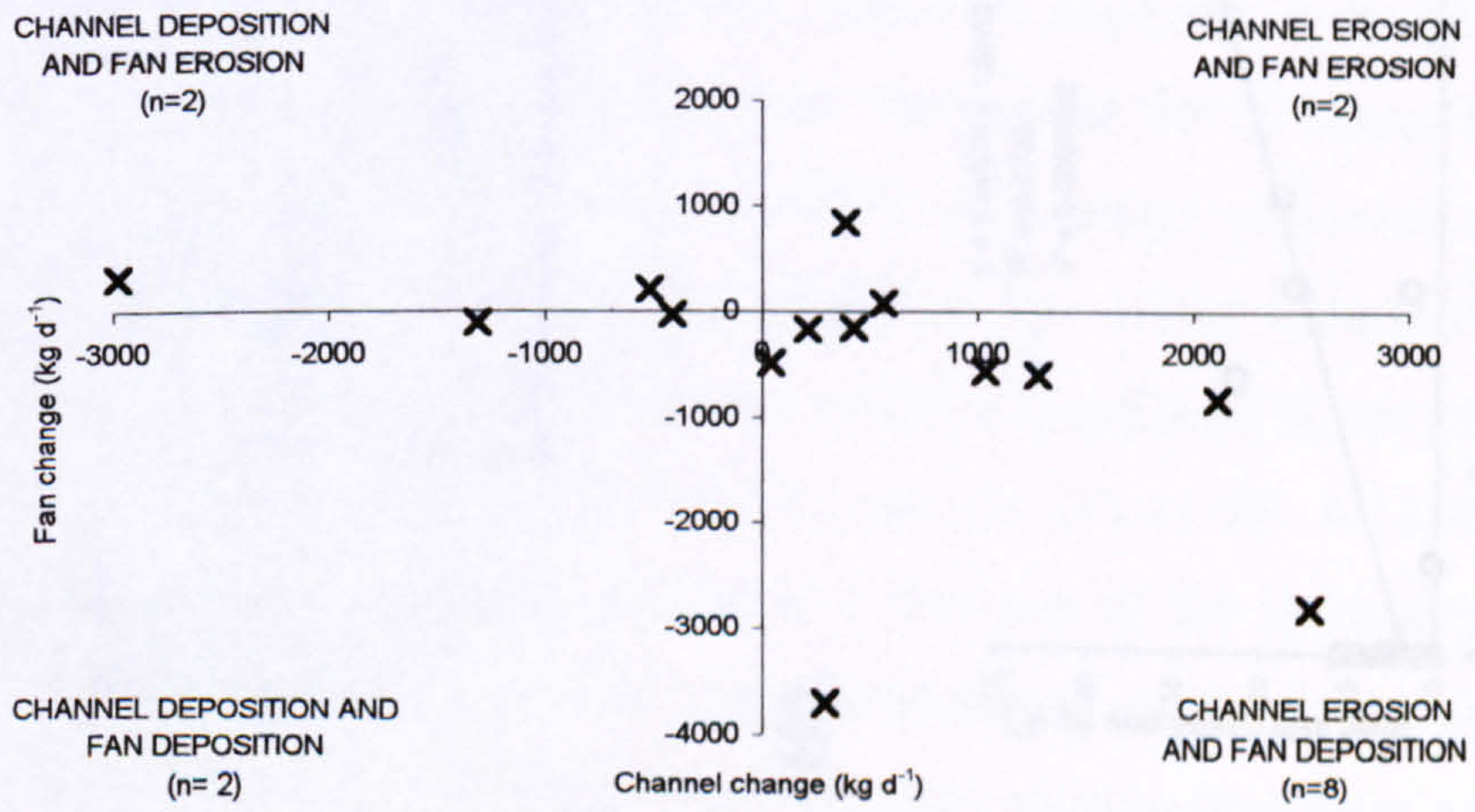
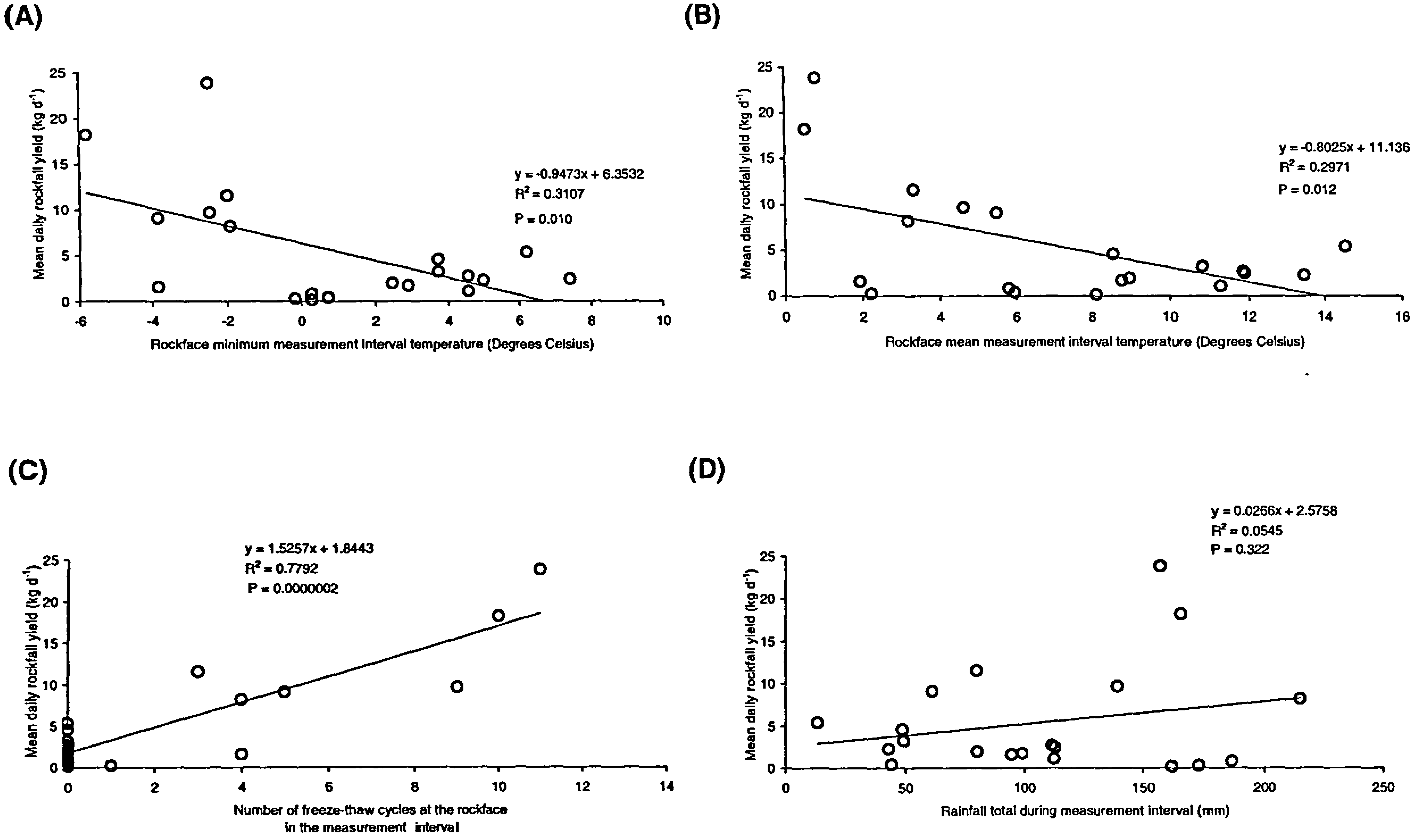


Figure 5.13: Relationship between rockfall yields and meteorological conditions: (A) minimum temperature, (B) mean temperature, (C) freeze-thaw cycles, (D) total rainfall



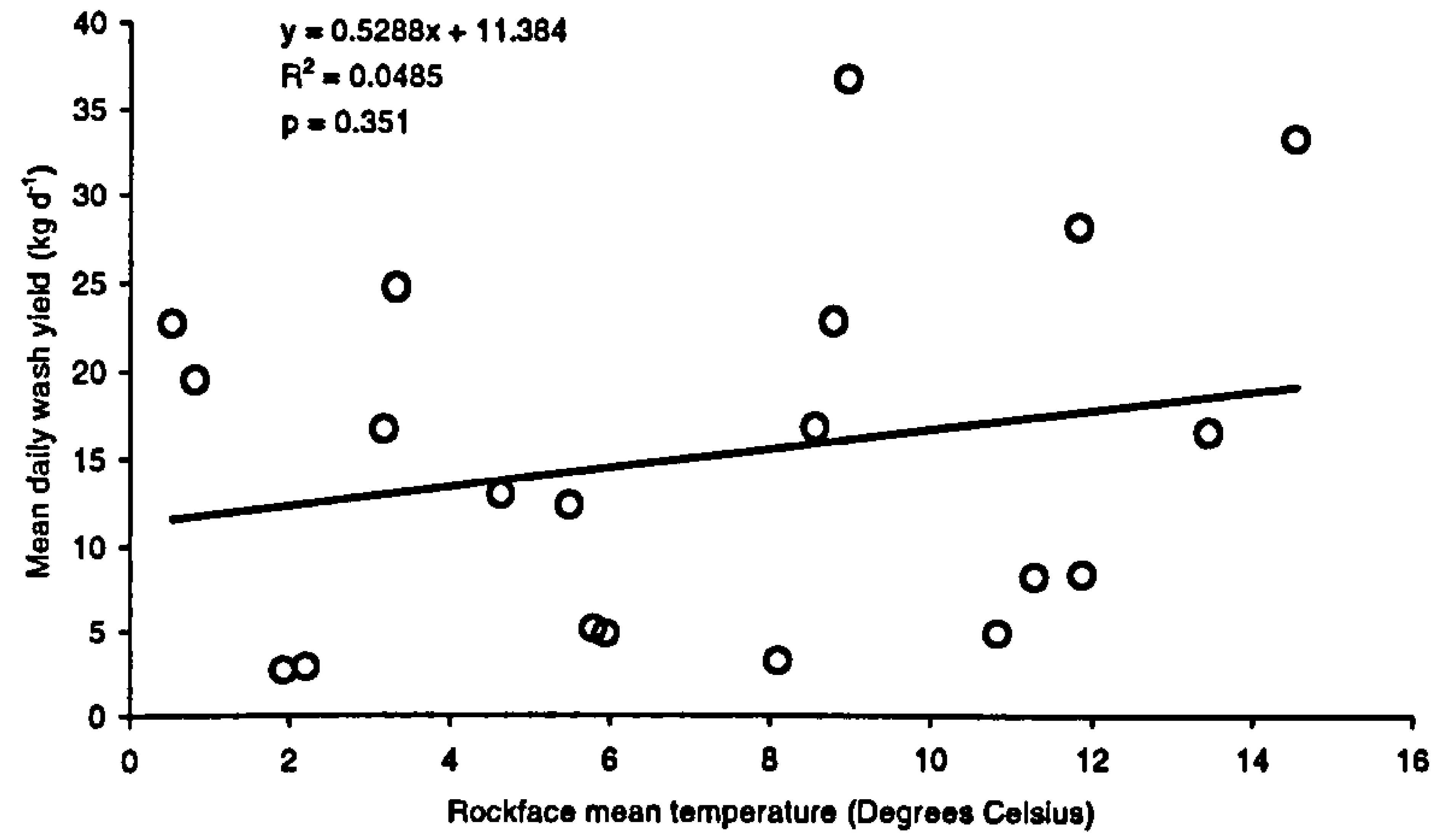
rockfall shattering a correlation with total rainfall is also presented. This shows significant scatter, and returns a very weak positive correlation ($y = 0.0266x + 2.578$) with an R^2 of 0.0545 ($p < 0.322$). It therefore appears that freeze-thaw activity and not rainfall significantly influence rockfall activity at Iron Crag. This finding provides additional explanation for the rockfall yields shown in Figure 5.9 (B).

Figure 5.14 plots the relationship between wash yields and meteorological conditions. The relationships are weak (R^2 values no greater than 0.065, and significance levels no better than 0.277), from which it is concluded that wash yields are not controlled by a simple relationship with meteorological conditions. Some other factor, or combinations of factors, perhaps parent material must also play a role. Furthermore, the definition of wash processes adopted here will be partly responsible, as is it a 'catch-all' for surface sediment movements and as such includes a combination of process types; many of which will have unique correlations with meteorological data. For example inter-rill wash will occur with the generation of runoff whilst dry ravel as it names suggests will take place under dry conditions, be these warm or cold.

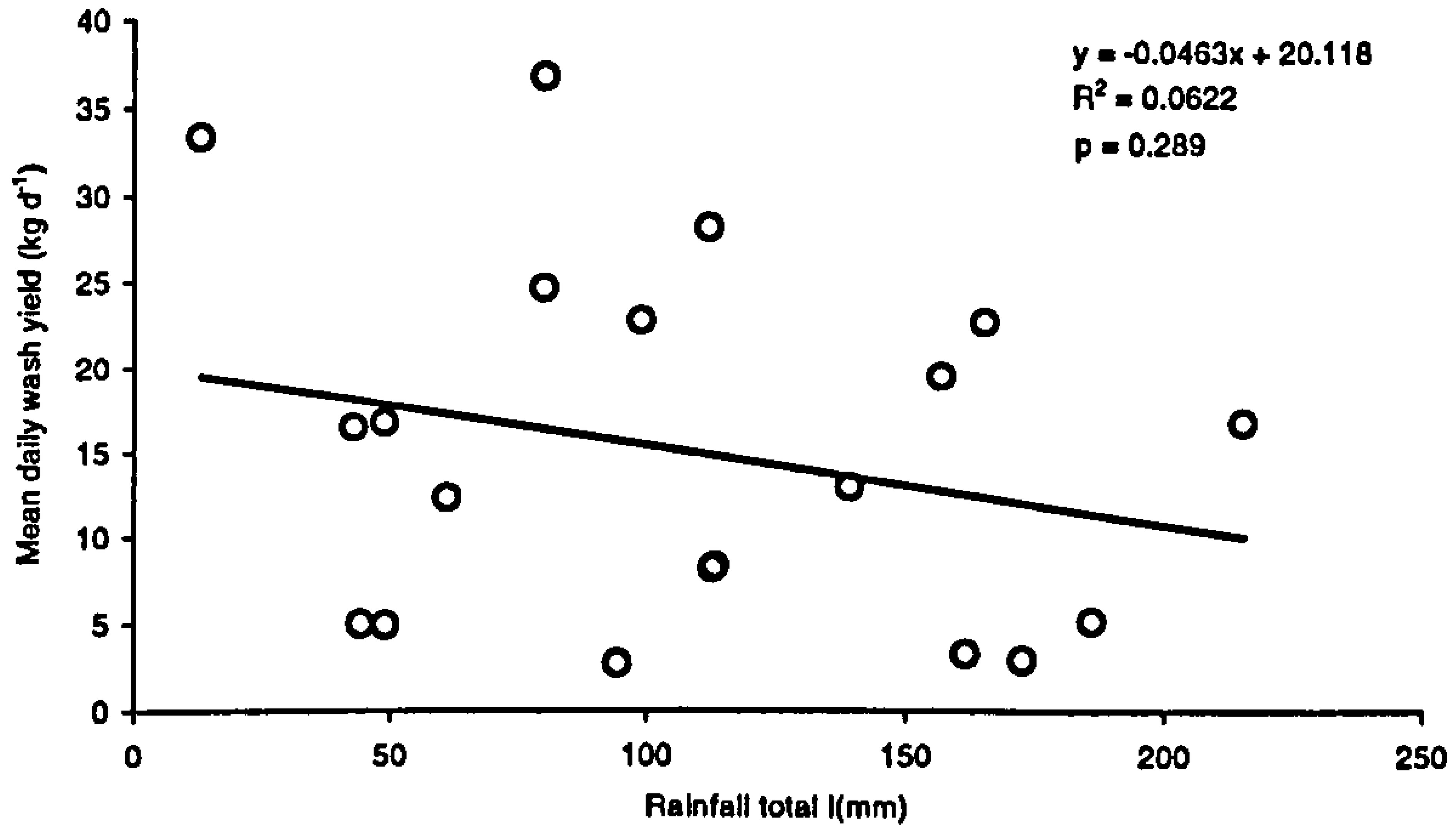
Figure 5.15 considers bank erosion, but owing to the small number of measurements ($n= 6$) the trends drawn are considered provisional, requiring further detailed investigation. Comparing bank yield with mean temperature reveals significant scatter and poor correlations ($R^2 = 0.0033$, $p= < 0.914$) (Figure 5.15-A). Stronger relationship between bank erosion yield and rainfall is shown in Figure 5.15 B-D. Surprisingly bank erosion yield increases with declining total rainfall (R^2 0.525, $p < 0.104$). This is misleading as bank erosion would be expected to be greater with higher rainfall, as the implications of this would be greater fluvial action at the base of banks, and the greater likelihood of positive pore water pressures leading to failure of the bank material. This trend is explained by careful examination of the data producing the greatest yields, since both relate to significant storm periods (i.e. measurement interval 13 [12.6.99- 28.6.99], and 22 [11.11.99- 4.12.99]) where yields were high, and the low total rainfall is a function of the short measurement intervals. Hence the small data set and way of describing rainfall is responsible for this potentially misleading relationship. More realistic relationships exist with the

Figure 5.14: Relationship between wash yields and meteorological conditions: (A) mean temperature, (B) total rainfall, (C) maximum rain intensity

(A)



(B)



(C)

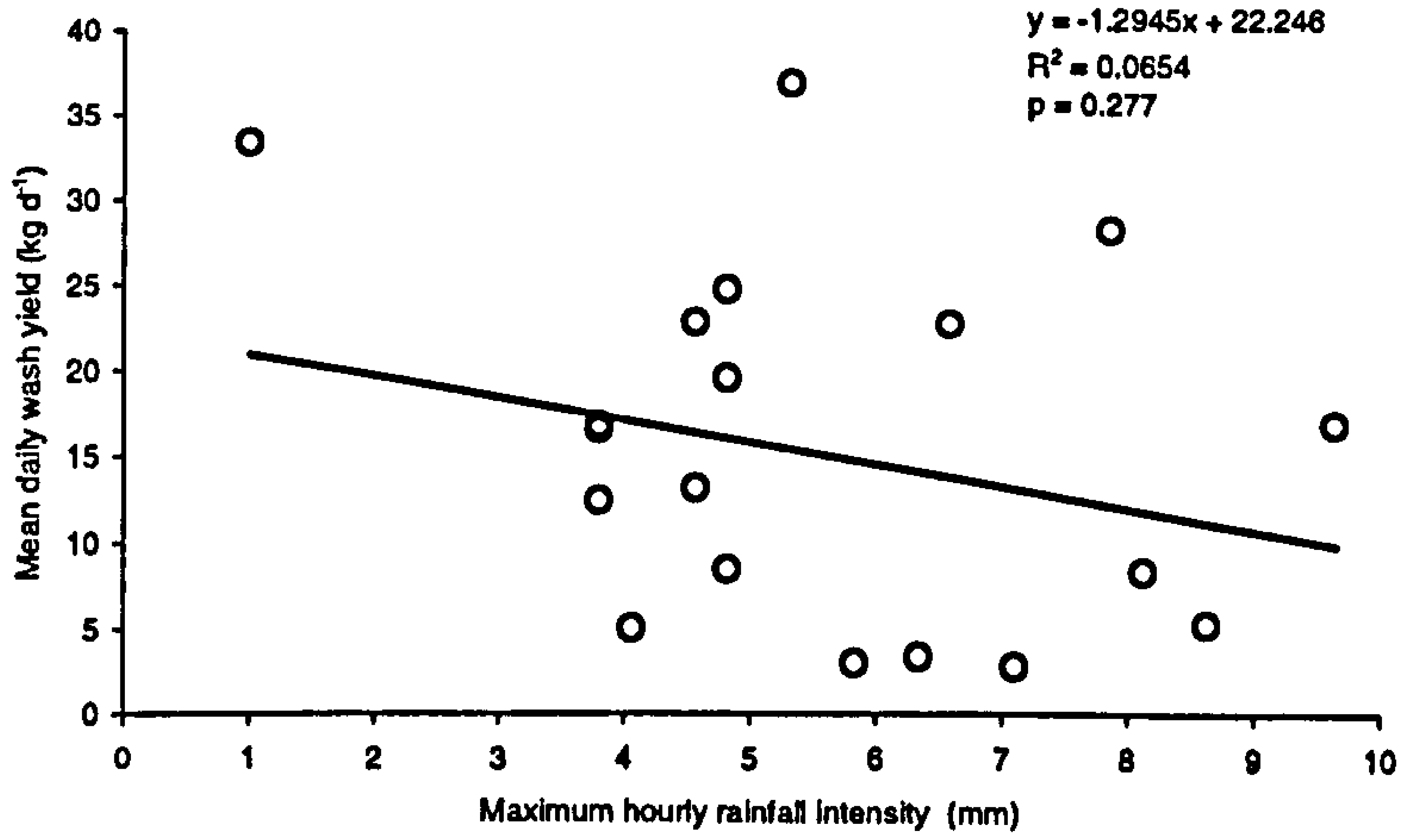
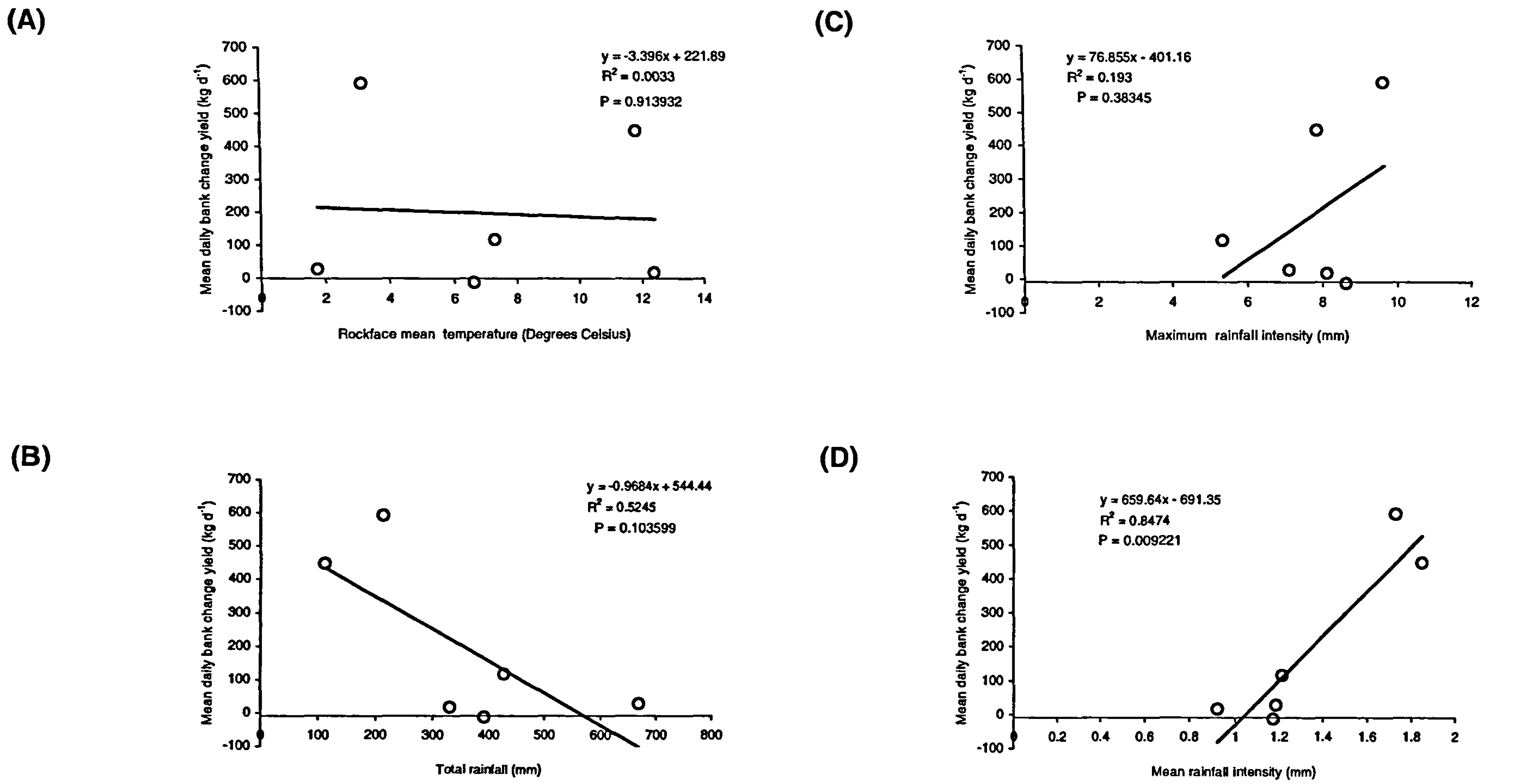


Figure 5.15: Relationship between bank erosion/ deposition and meteorological conditions:
(A) mean temperature, (B) total rainfall, (C) maximum hourly intensity, (D) mean hourly intensity



rainfall intensity, where maximum hourly intensity positively correlates with yield, although this is weak (R^2 0.193, $p < 0.383$) compared to mean rainfall intensity (R^2 of 0.847, $p < 0.009$). Taken together these trends suggest some hydro-meteorological control of bank erosion.

Figure 5.16 gives the relationship between net channel change and total rainfall, with depositional and erosional channel change plotted separately. Both relationships suggest similar behaviour, of decreased deposition and increasing erosional activity with greater rainfall (net erosion R^2 0.2318, $p < 0.159$, net deposition R^2 0.9834, $p < 0.082$) . It is probable that greater rainfall totals result in larger and longer periods of channel discharge enabling the transport of sediment through the system. However the fact that under similar quantities of rainfall the channel can display either a net depositional or erosional change suggests a more complicated system.

Figure 5.17 focuses on the net deposition of the fan surface, as this is the dominant behaviour of this component, i.e. it is primarily a sediment sink. All three charts show rates of deposition to be greater with larger total and more intense rainfall, and are confirmed to be statistically significant between $p < 0.0007$ and 0.0039. This suggests that under these conditions the input of material from the channel is greater, which Figure 5.16 showed to be the case. This finding further supports the linkage between the channel and fan components identified in Figure 5.12. The relationships are strongly influenced by two large deposition events occurring towards the end of the measurement period.

Examining the dominant meteorological conditions (as outlined in Chapter 4) provides a second means of explaining the temporal behaviour of the sediment system. Measurement intervals dominated by dry ravel are termed summer dry periods, to provide a distinct meteorological classification (Table 5.14) rather than the mixed process- meteorological classification as presented in Chapter 4.

Figure 5.16: Relationship between channel change and total rainfall

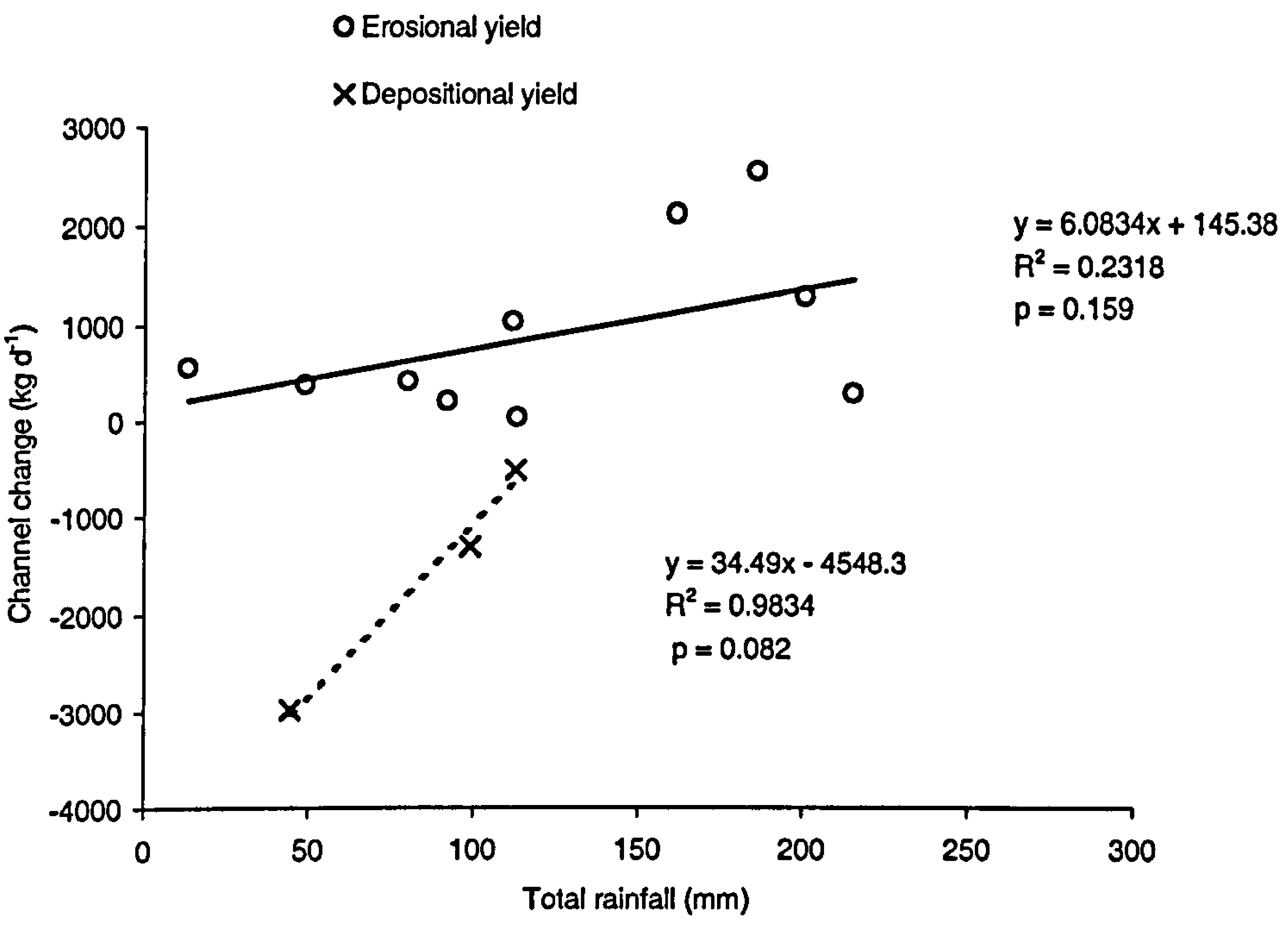
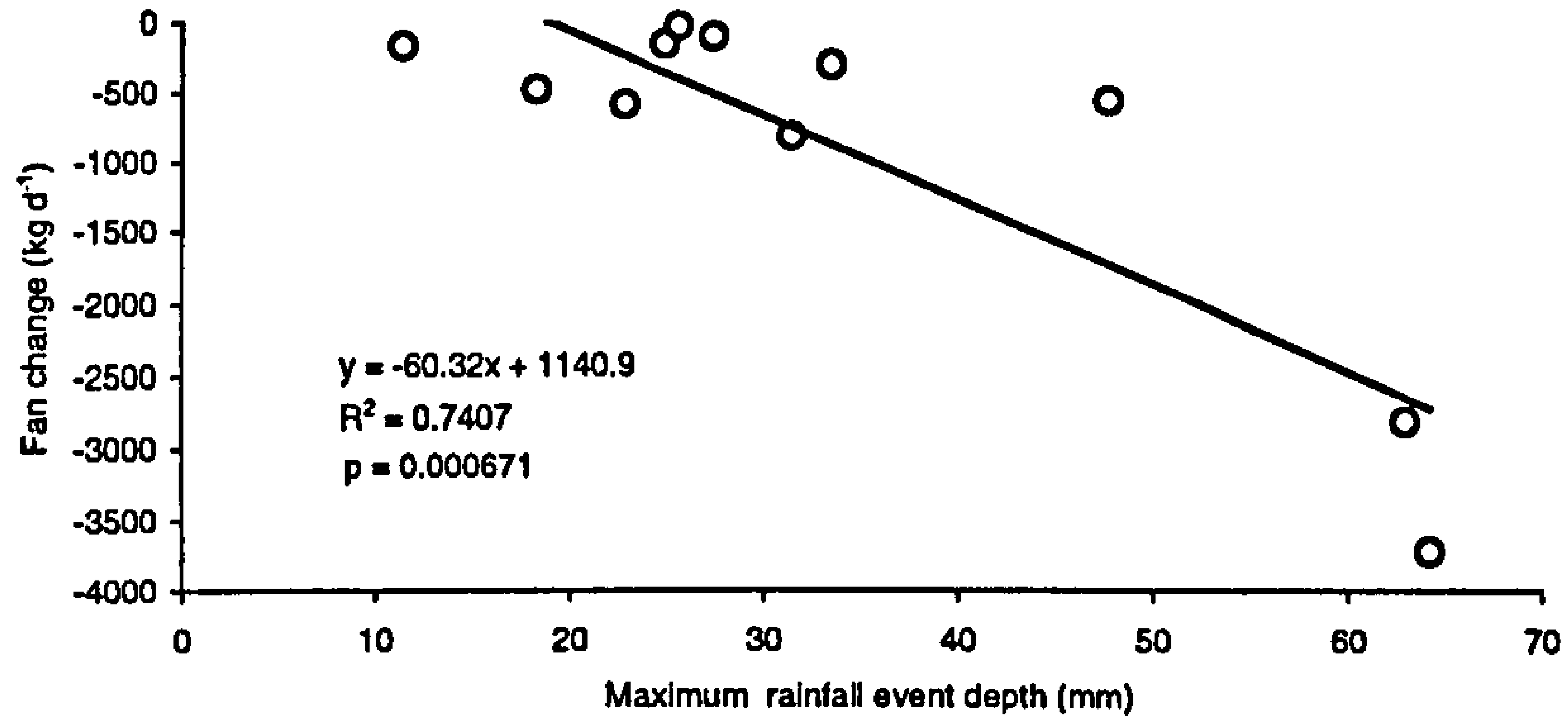
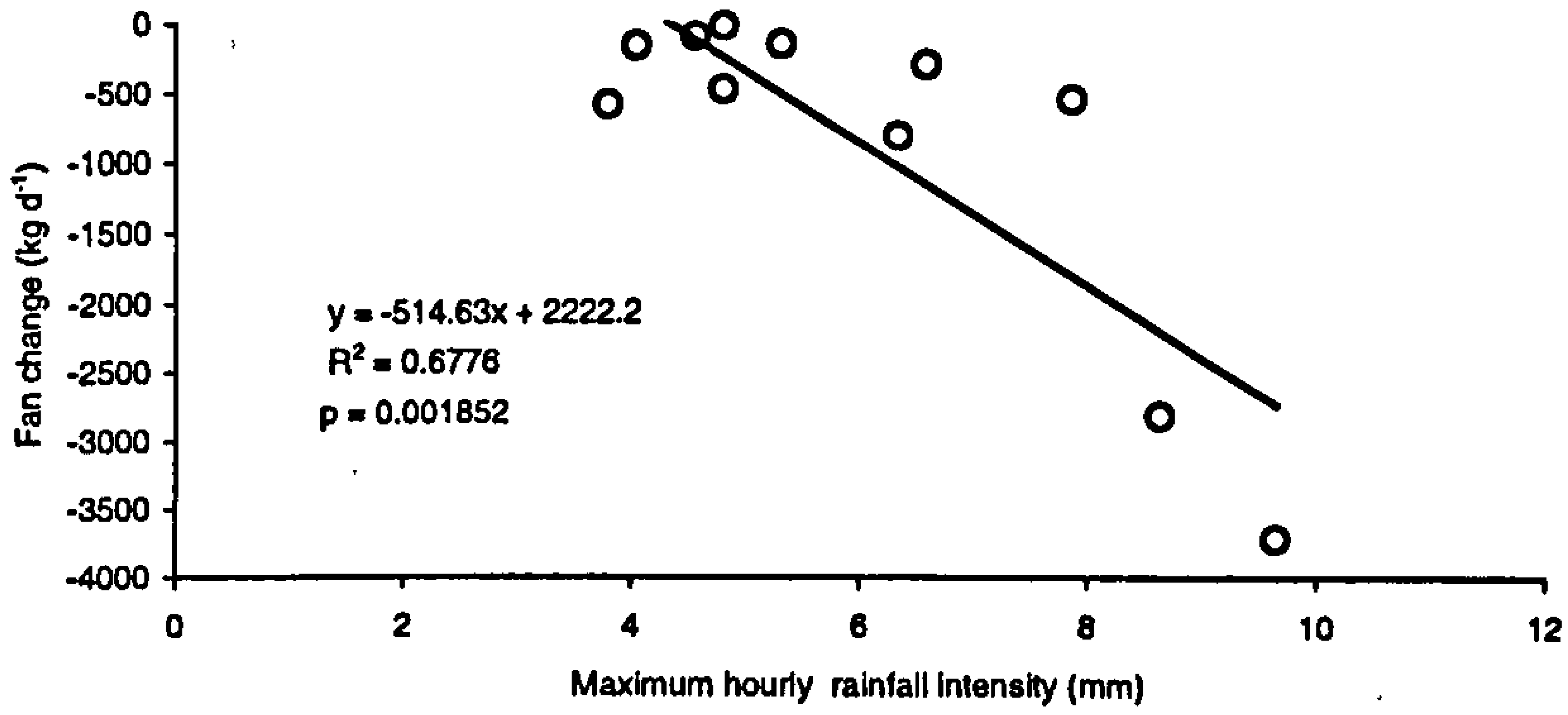


Figure 5.17: Relationship between fan sedimentation and meteorological conditions (A) maximum event rainfall, (B)maximum rainfall intensity, (C) total rainfall

(A)



(B)



(C)

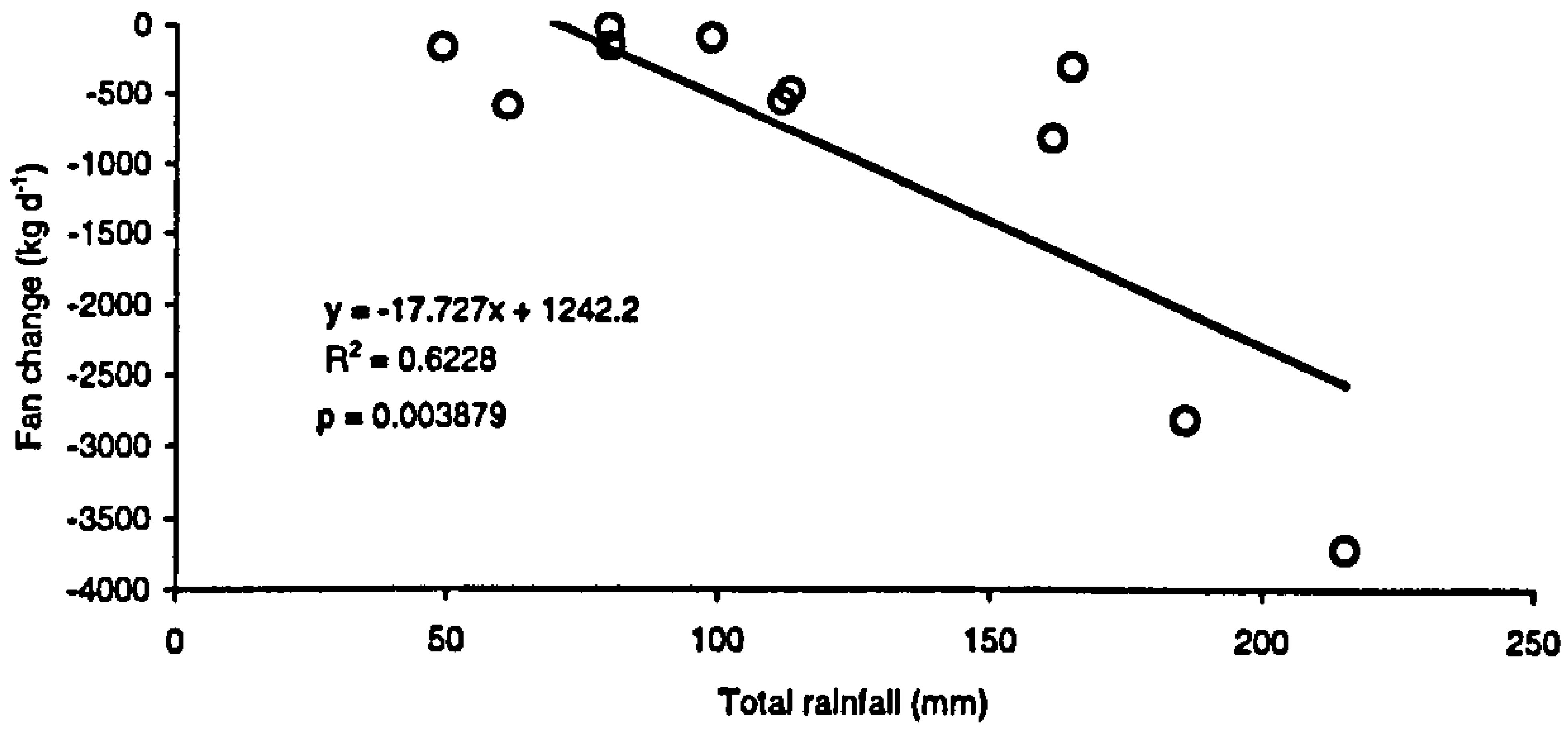
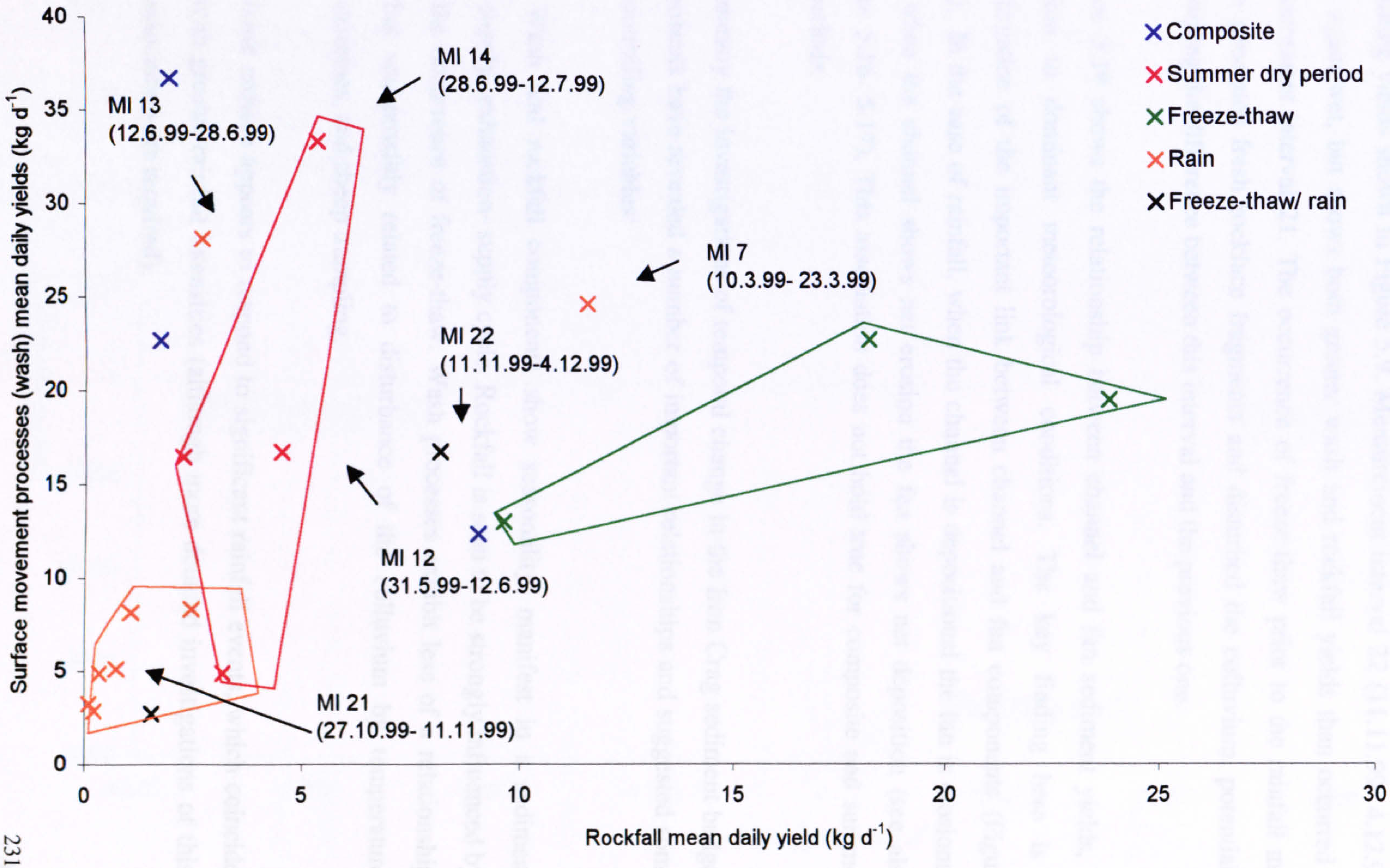


Figure 5.18 shows the relationship between mean daily yields, from surface movement processes (wash) and rockfall, classified according to the dominant meteorological conditions. Important differences, and exceptions, exist between the clusters. Most significantly rainfall and freeze-thaw dominated measurement intervals form separate clusters. In terms of mean daily yield rainfall appears to be a less important meteorological condition for hillslope activity than freeze-thaw temperature cycles. Rainfall produces greater wash yields than rockfall activity, but both are generally less than that produced by freeze-thaw. Freeze-thaw's greatest impact is in the generation of higher rockfall yields (see Figure 5.13, C).

Summer dry periods exhibit limited variability in rockfall yields, but considerable variability in surface process yields. Field observations indicate that dry ravel flows (28.6.99 to 12.7.99) and the disintegration of a previous freeze-thaw crust (31.5.99 to 12.6.99) yield an abundance of granular material. The localised nature of these activities probably accounts for the variability in surface process yields during the summer dry periods. Higher levels of surface movement process activity during the summer provide some explanation for the weak relationships shown in Figure 5.14. Generally yields are greater with warmer temperatures and less rainfall. Also the occurrence of higher yields in conjunction with summer dry periods and freeze-thaw adds support to the previously stated hypothesis that sediment conditions rather than rainfall controls wash yields.

Notable exceptions to the general clusters occur. Measurement interval 7 (10.3.99-23.3.99) and 13 (12.6.99- 28.6.99) are both rainfall dominated periods, producing far greater wash yields than the norm; and in the case of measurement interval 7 higher rockfall yield as well. Measurement interval 7 followed an interval dominated by freeze-thaw activity so abundant loose material may have been available in the system. Measurement interval 13 contained a significant rainstorm creating fresh rills and sheetflow. Prior to this conditions were dry and dominated by dry ravel, hence an inheritance of available material may be an important factor in helping to explain these elevated yields. So a combination of material characteristics and transport capacities are the likely causes of these anomalies.

Figure 5.18: Rockfall and surface movement process mean daily yields classified according to the dominant meteorological conditions during a particular measurement interval



Measurement interval 21 (27.10.99- 11.11.99) was a particularly wet one, but there were low yields of wash and rockfall. In the case of rockfall, high yields are not expected, as no freeze-thaw activity precedes this interval. Of more importance is the low wash yield, despite the high transport capacity, probably reflecting a lack of available sediment. This hypothesis of sediment exhaustion is reflected in the declining yields shown in Figure 5.9. Measurement interval 22 (11.11.99- 4.12.99) was again wet, but shows both greater wash and rockfall yields than occurred in measurement interval 21. The occurrence of freeze-thaw prior to the rainfall may have generated fresh rockface fragments and disturbed the colluvium, potentially explaining the difference between this interval and the previous one.

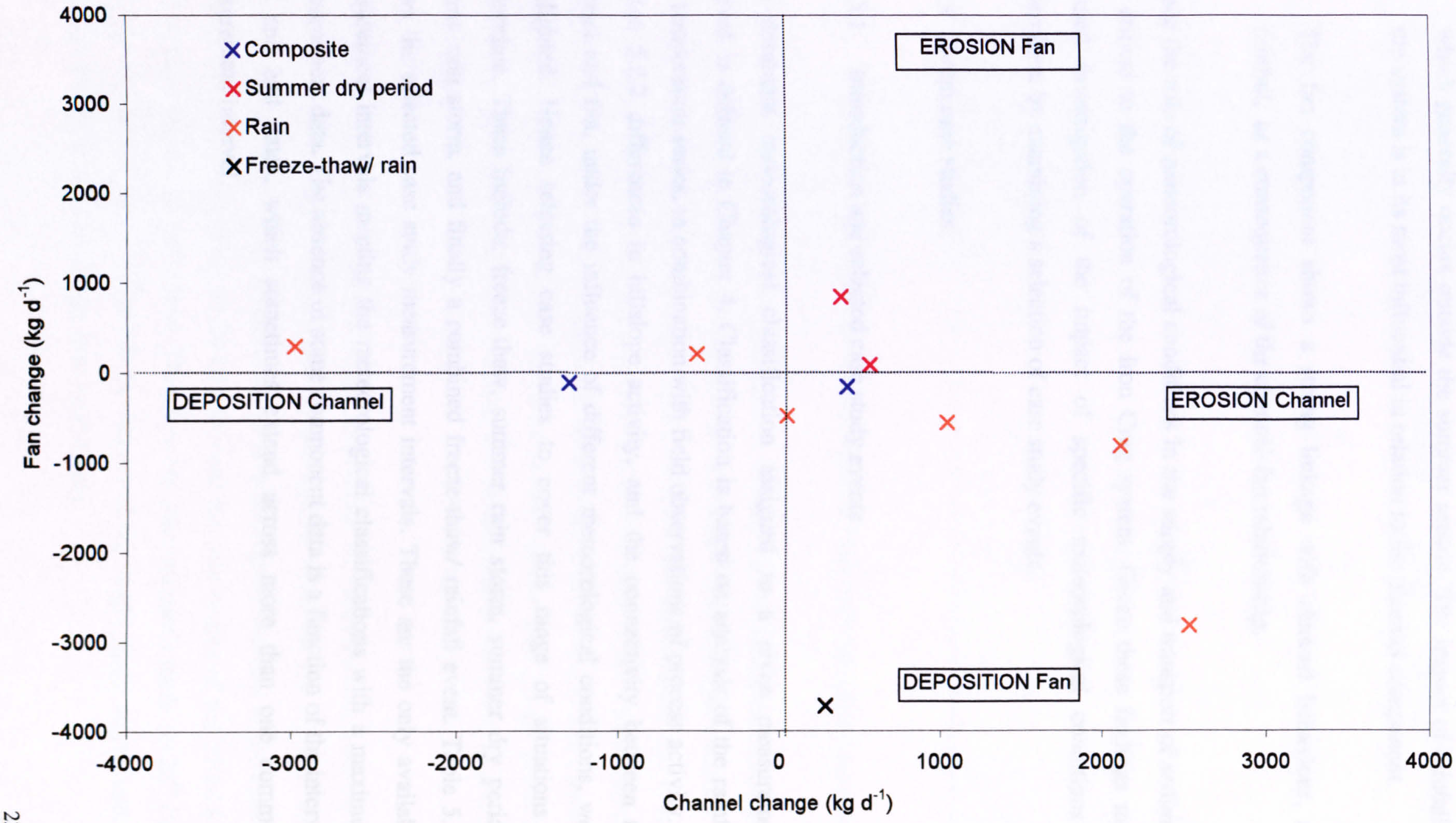
Figure 5.19 shows the relationship between channel and fan sediment yields, in relation to dominant meteorological conditions. The key finding here is a confirmation of the important link between channel and fan components (Figure 5.12). In the case of rainfall, when the channel is depositional the fan is erosional, and when the channel shows net erosion the fan shows net deposition (see also Figure 5.16- 5.17). This association does not hold true for composite and summer dry periods.

In summary the investigations of temporal change in the Iron Crag sediment budget components have revealed a number of important relationships and suggested some key controlling variables:

a) Wash and rockfall components show seasonality, manifest in a sediment supply- exhaustion- supply cycle. Rockfall is seen to be strongly influenced by the occurrence of freeze-thaw. Wash processes exhibit less of a relationship but are possibly related to disturbance of the colluvium by temperature extremes, and sheep trampling.

b) Bank erosion appears to respond to significant rainfall events, which coincide with greater rainfall intensities (although more detailed investigations of this association are required).

Figure 5.19: Channel and fan mean daily changes classified according to the dominant meteorological conditions in a measurement interval



c) The channel shows the greatest stability during the summer and conversely the greatest variability at other times. Most erosion coincides with higher rainfall, which generally occurs outside the summer season. The impact of rainfall on the system is at its most influential in relation to the channel component.

d) The fan component shows a strong linkage with channel behaviour, and rainfall, as a consequence of the channel-fan relationship.

Hence the role of meteorological conditions in the supply and transport of sediment are critical to the operation of the Iron Crag system. Given these findings more detailed investigation of the impact of specific meteorological conditions is undertaken, by examining a selection of case study events.

5.2.3 Event case studies

5.2.3.1 Introduction and selected case study events

The dominant meteorological classification assigned to a given measurement interval, is defined in Chapter 4. Classification is based on analysis of the rainfall and temperature series, in combination with field observations of process activity. In section 5.2.2 differences in hillslope activity, and the connectivity between the channel and fan, under the influence of different meteorological conditions, were highlighted. Hence selecting case studies to cover this range of situations is appropriate. These include: freeze-thaw, summer rain storm, summer dry period, autumn rain storm, and finally a combined freeze-thaw/ rainfall event. Table 5.14 shows the selected case study measurement intervals. These are the only available measurement intervals meeting the meteorological classifications with a maximum of component data. The absence of some component data is a function of the interval start and end dates, which sometimes extend across more than one common measurement interval.

Table 5.14: Case study event types selected from the Iron Crag sediment budget monitoring data series, indicating the availability of component data.

Case study event	Wash	Rockfall	Bank erosion	Channel	Fan
MI 6 (11.2.99-10.3.99) (Freeze-Thaw)	✓	✓	✖	✖	✓
MI 13 (12.6.99-28.6.99) (Summer storm)	✓	✓	✓	✓	✓
MI 14 (28.6.99-12.7.99) (Summer dry period)	✓	✓	✖	✓	✓
MI 21 (27.10.99-11.11.99) (Autumn storm/ Debris flow)	✓	✓	✖	✓	✓
MI 22 (11.11.99- 4.12.99) (Freeze- thaw and winter storm)	✓	✓	✓	✓	✓

5.2.3.2 Meteorological conditions of selected case study measurement intervals

Before viewing the geomorphological impacts in each case study, the meteorological conditions of each measurement interval are outlined. More detailed analyses are given in Chapter 4. Figure 5.20 and Table 5.15 show the temperature and rainfall conditions for measurement interval 6 (11.2.99-10.3.99), from which multiple freeze-thaw cycles are evident. Rainfall is often of short duration and low intensity. Some of the rain is more likely to be snowmelt in the rain gauge given the occurrence of two known snowfalls during this measurement interval (21- 22.2.99, and 6- 8.3.99).

Figure 5.21 and Table 5.15 outline the conditions in measurement interval 13 (12.6.99- 28.6.99), which is dominated by one rainfall event on 19- 20.6.99. Field observations on 26.6.99 record significant geomorphological changes in the system. Subsequent field observations on 28.6.99 showed the rain events of the 27-28.6.99 had no major impact on the system. Therefore the measurements made on 28th June 1999 can be reliably used to illustrate the impact of the single major storm, and do not represent the composite impact of several events.

Figure 5.22 and Table 5.15 illustrate the general absence of rainfall between 28.6.99 and 12.7.99. Correspondingly there are higher temperatures with large diurnal variation, suggesting the occurrence of clear skies allowing rapid heating and cooling of the air.

Figure 5.23 and Table 5.15 show measurement interval 21 (27.10.99- 11.11.99) was very wet being dominated by three prolonged periods of rainfall in the first week of November 1999. The rainfall events also achieved hourly intensities in excess of 8 mm. The most significant of the three notable rainfall events was on 4 -5.11.99, though whether the debris flow which occurred in this measurement interval, relates to this or the previous rain event (1.11.99) is not directly documented. The bedload movement logger at micro cross section 10 was tripped at 13:55 on the 1.11.99, and corresponds with a moderately high hourly rainfall intensity (5.60 mm) recorded between the 13:00 to 13: 59.

Figure 5.24 and Table 5.15 shows the start of the last measurement interval (11.11.99- 4.12.99) to be relatively dry, but increasingly cold with frosts. Field observations at the start of this cold spell (17.11.99) identified frost action in the form of needle ice on channel banks, and the freezing of the channel bed and fan surface. However, later in November 1999 temperatures increased above 0 °C, and this was associated with multiple rainfall events. Particularly relevant was the rain event of 27- 28.11.99 which was both long and for periods exhibited hourly rainfall intensities in excess of 6 mm h^{-1}. Field observations on 29.11.99 identified noticeable channel and fan changes. Rainfall events after this time appeared to have no further impact on the system, though field observations were limited owing to snow cover.

Figure 5.20: Meteorological conditions for measurement interval 6 (11.2.99- 10.3.99) , at Iron Crag head (570m O.D.)

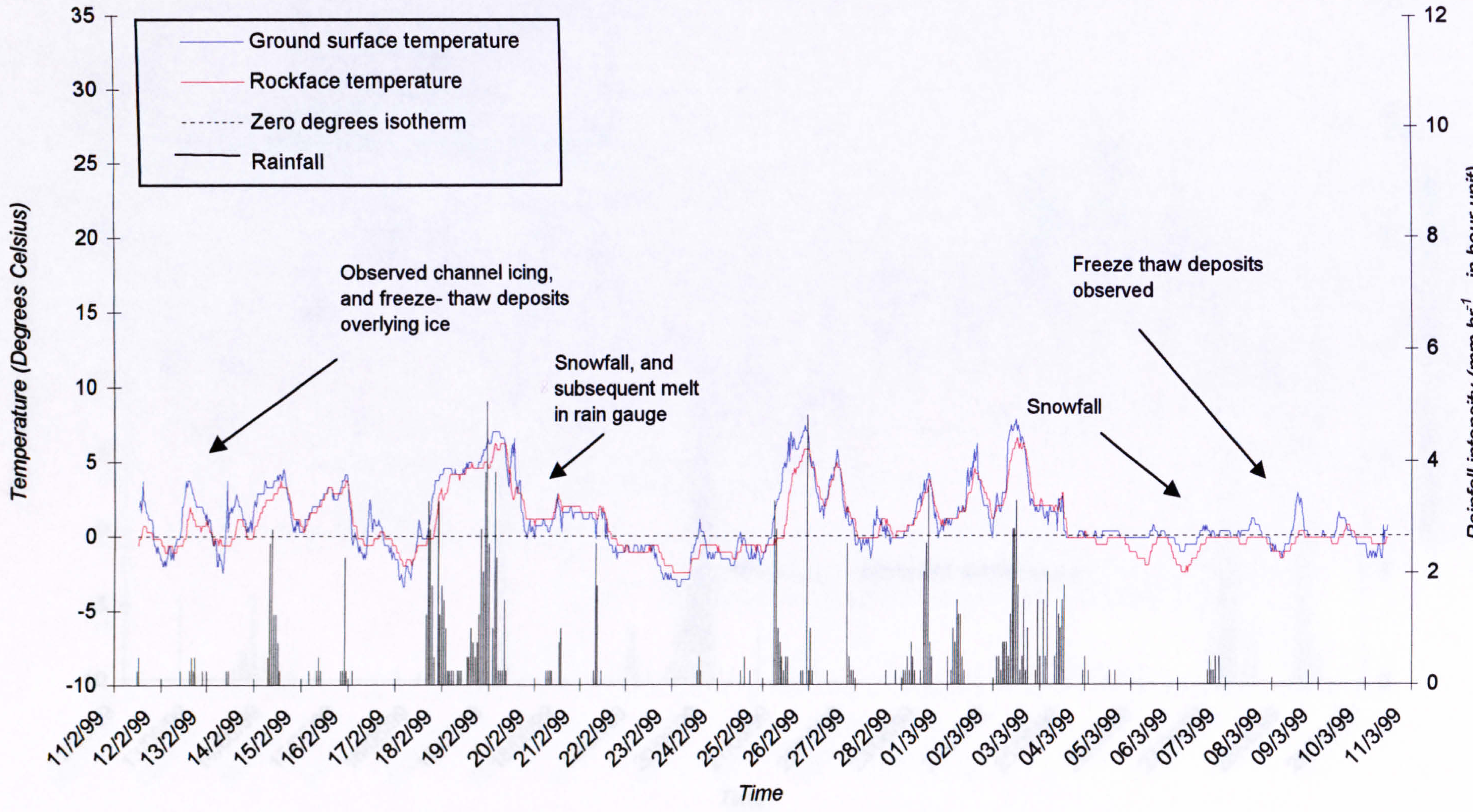


Figure 5.21: Meteorological conditions for measurement interval 13 (12.6.99- 28.6.99), at Iron Crag head (570m O.D.)

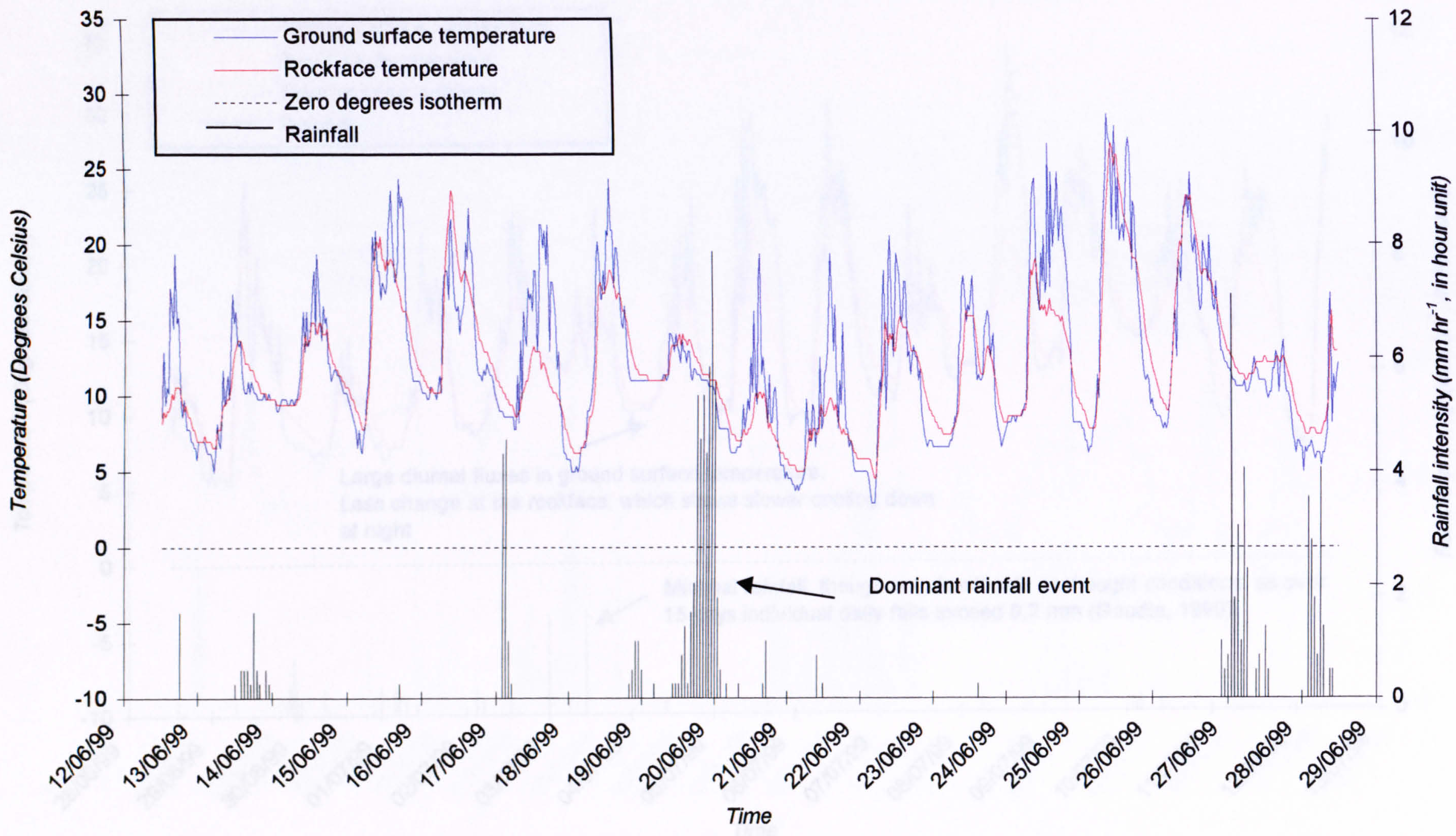


Figure 5.22: Meteorological conditions for measurement interval 14 (28.6.99- 12.7.99), at Iron Crag head (570m O.D.)

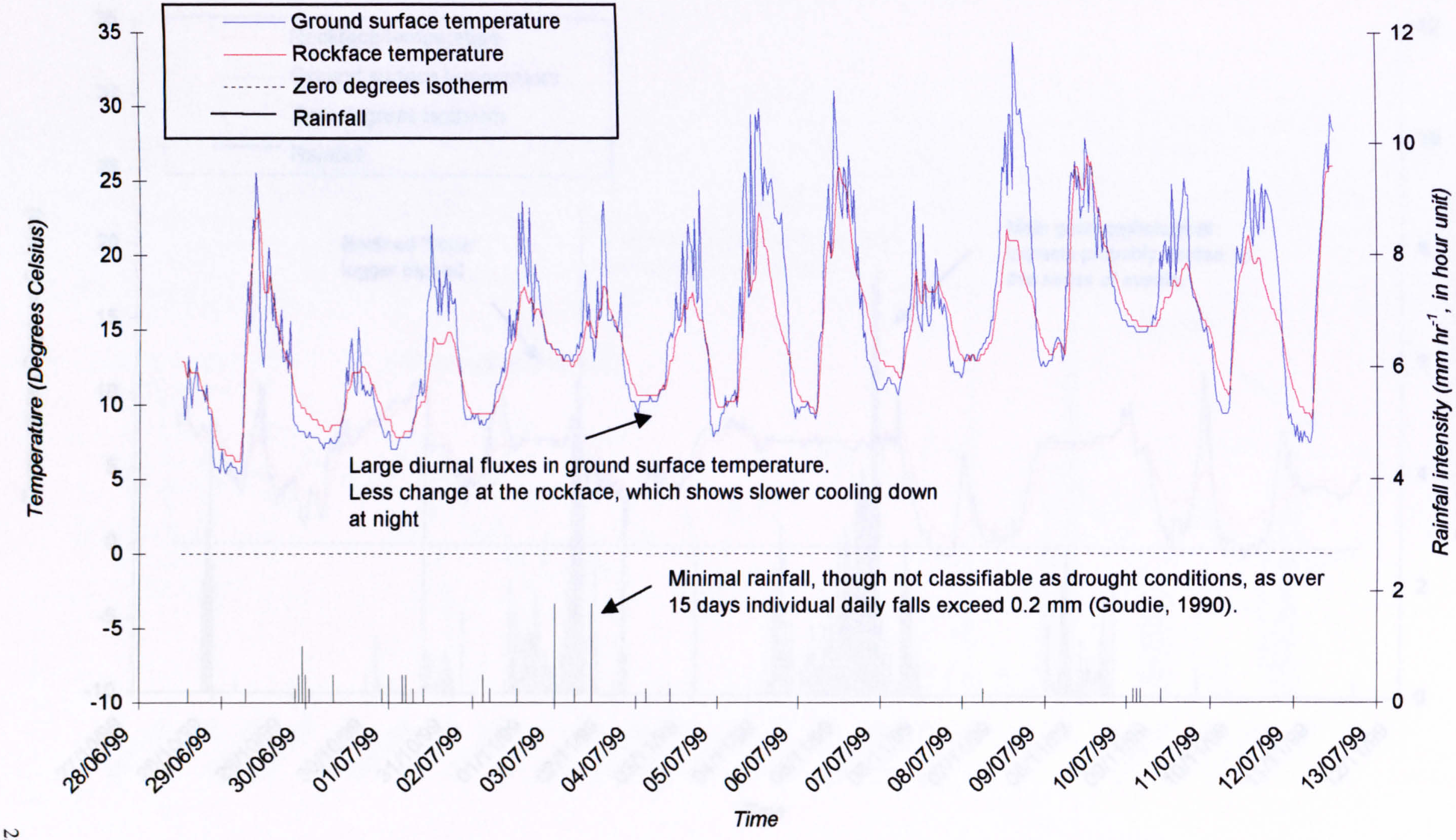


Figure 5.23: Meteorological conditions for measurement interval 21 (27.10.99- 11.11.99), at Iron Crag head (570m O.D.)

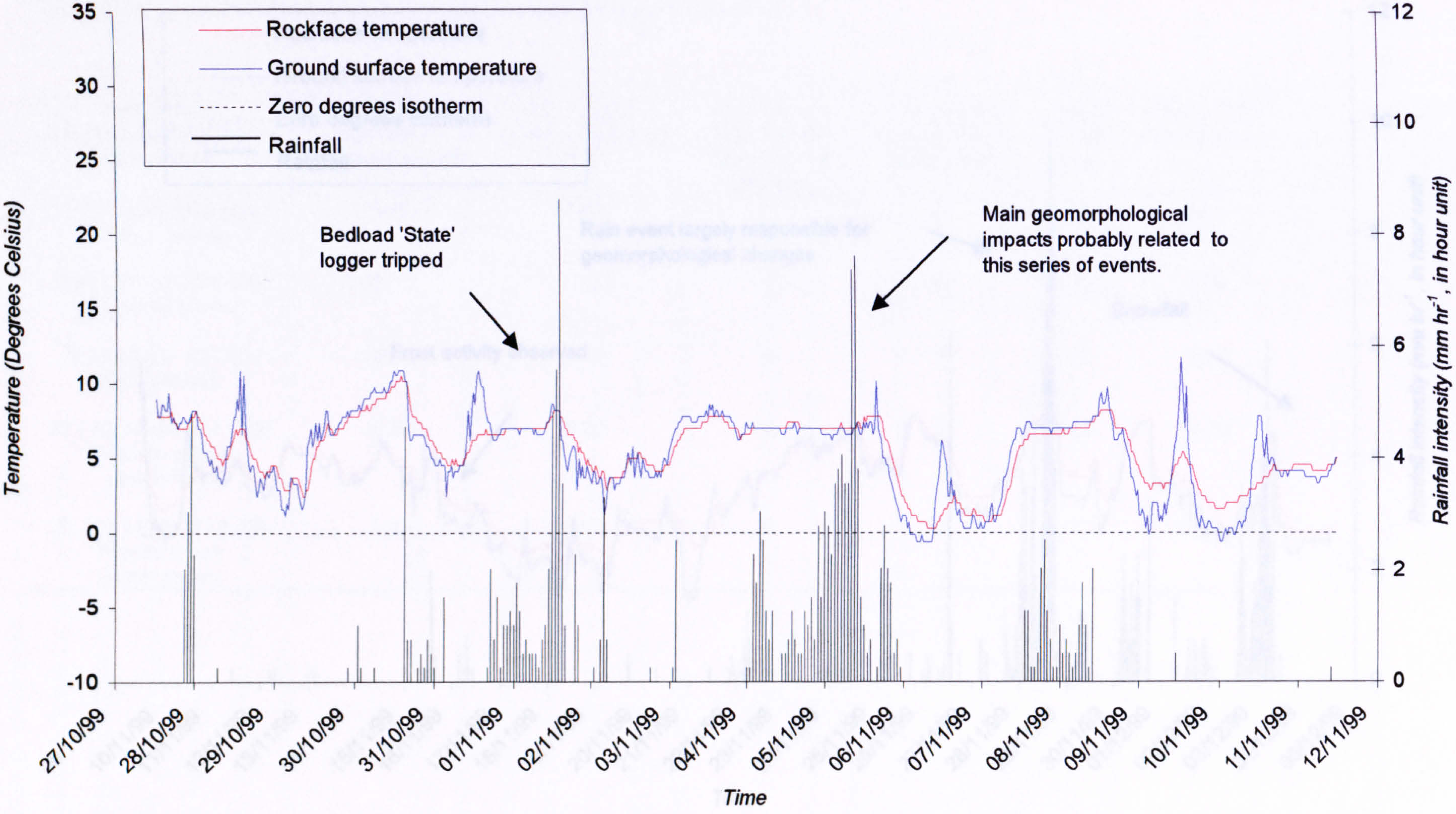


Figure 5.24: Meteorological conditions for measurement interval 22 (11.11.99- 4.12.99), at Iron Crag head (570m O.D.)

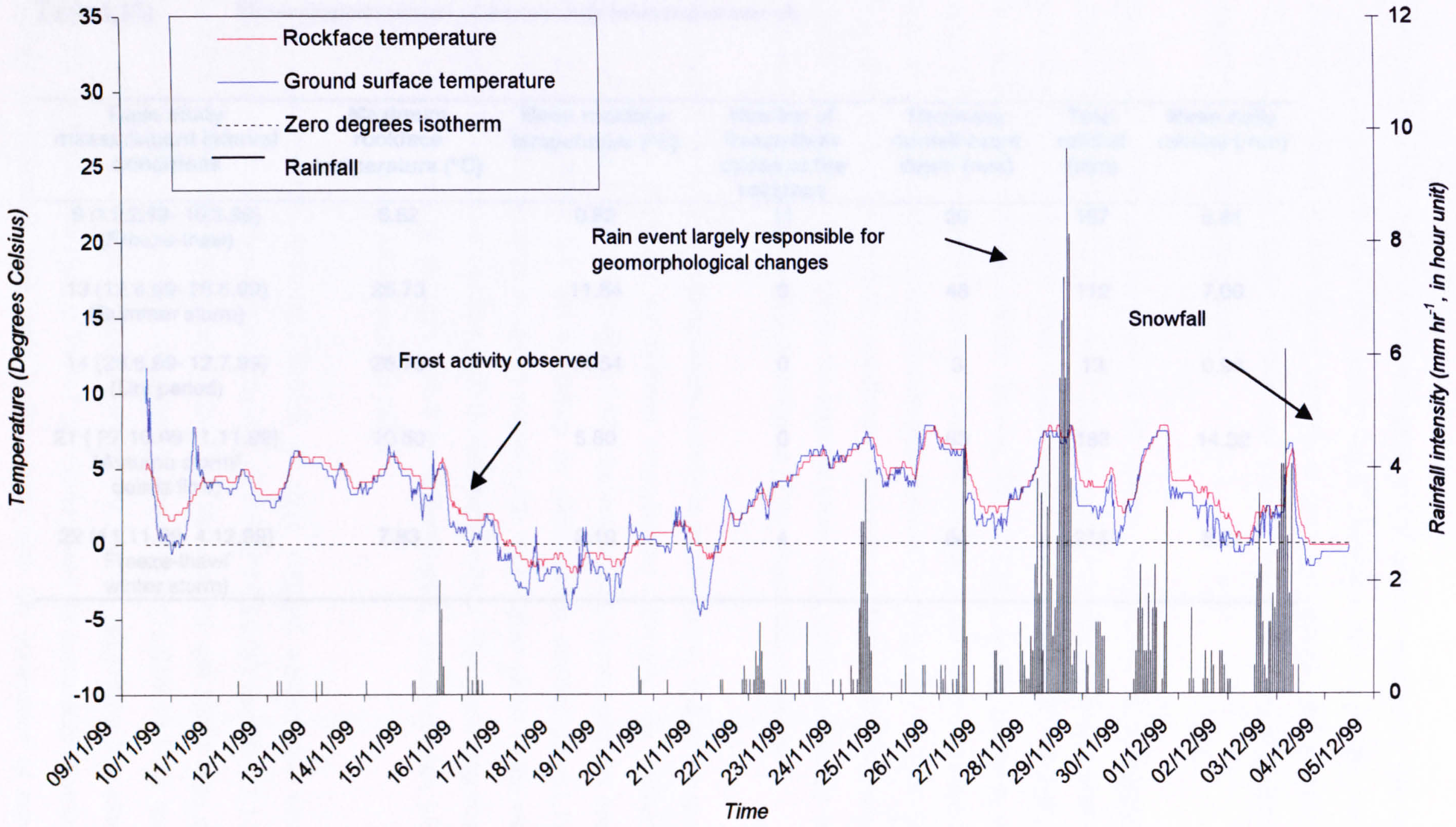


Table 5.15: Meteorological summary of the case study measurement intervals

Case study measurement interval conditions	Maximum rockface temperature (°C)	Mean rockface temperature (°C)	Number of freeze-thaw cycles at the rockface	Maximum rainfall event depth (mm)	Total rainfall (mm)	Mean daily rainfall (mm)
6 (11.2.99- 10.3.99) (Freeze-thaw)	6.62	0.82	11	20	157	5.81
13 (12.6.99- 28.6.99) (Summer storm)	26.73	11.84	0	48	112	7.00
14 (28.6.99- 12.7.99) (Dry period)	26.73	14.54	0	3	13	0.94
21 (27.10.99 11.11.99) (Autumn storm/ debris flow)	10.60	5.80	0	63	186	14.32
22 (11.11.99- 4.12.99) Freeze-thaw/ winter storm)	7.83	3.19	4	64	216	8.61

5.2.3.3 The impact of major meteorological events on local sediment yields

The impact of the dominant meteorological events are investigated on two levels. Firstly the overall rates of daily activity (kg d^{-1}) between case studies are outlined. Secondly, a more detailed spatial analysis of intra component/ zone variability is conducted, in units of mass- per unit area- per day (kg m^{-2} d^{-1}), showing sediment production, storage and transport.

Figure 5.25 shows the response of all system components to meteorological conditions. Rockfall activity in the primary zone, is greatest during freeze-thaw conditions, with the highest yield in measurement interval 6 (11.2.99-10.3.99), and the second highest in measurement interval 22 (11.11.99-4.12.99). However, in the sub-primary and secondary hillslope zones this pattern is not observed; instead the greatest activity occurs during measurement interval 14 (28.6.99- 12.7.99) which was characterised by warm dry conditions. Furthermore, Table 5.16 illustrates, the number of days used to calculate the summer mean daily yields is relatively small, compared to the longer measurement interval of the winter measurements.

As stated in Section 5.2.2 wash process activity is more variable. Indeed the greatest yields for each zone are in different measurement intervals: the primary in measurement interval 14 (28.6.99-12.7.99); the sub primary in measurement interval 13 (12.6.99-28.6.99); and the secondary in measurement interval 22 (11.11.99-4.12.99). It is also possible to see an annual cycle with higher yields in the winter, declining throughout the summer, until the following winter. This again suggests that wash yields are not so strongly linked to meteorological conditions, but instead undergo a local supply and exhaustion effect.

Case study intervals involving rainfall all show channel erosion and net fan deposition. In both measurement intervals 13 (12.6.99-28.6.99) and 22 (11.11.99-4.12.99), rainfall has a far greater impact on the channel and banks than other components. In contrast to this measurement intervals 6 (11.2.99-10.3.99) and 14 (28.6.99-12.7.99) show net erosional change of the fan suggesting less channel activity. All this is confirmed in Table 5.16, which shows the percentage of sediment sourced from channels and banks to be greater with the occurrence of rainfall.

Figure 5.25: Case study component yield (kg d^{-1})

A: MI 6 (11.2.99- 10.3.99) Freeze-thaw
B: MI 13 (12.6.99- 28.6.99) Summer rain
C: MI 14 (28.6.99- 12.7.99) Summer dryness
D: MI 21 (27.10.99-11.11.99) Autumn rain/ Debris flow
E: MI 22 (11.11.99- 4.12.99) Freeze-thaw/ Rain

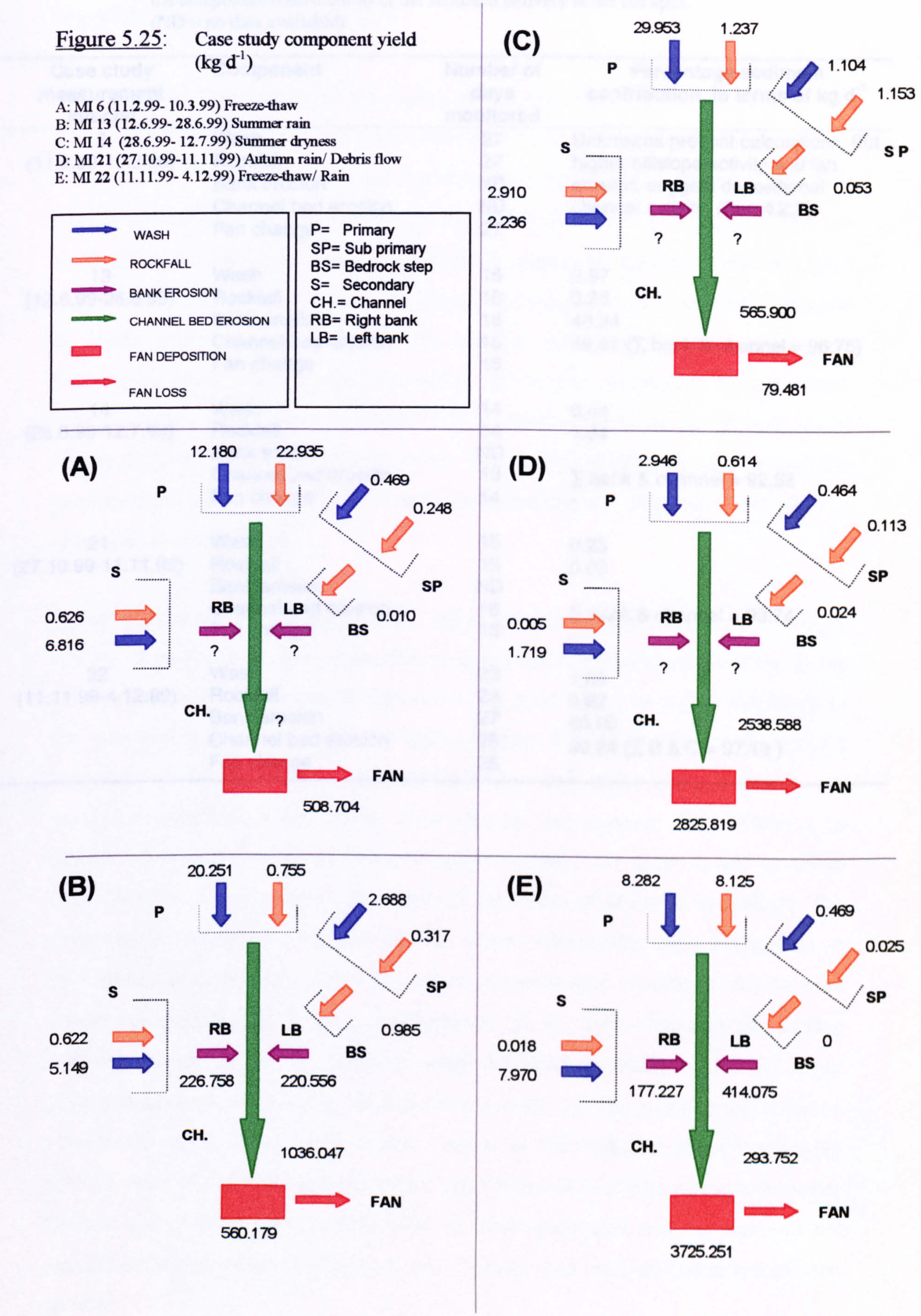


Table 5.16: Measurement interval length of data components expressed in Figure 4.26. Also showing the component contributions of the sediment delivery at the fan apex. (ND = no data available)

Case study measurement interval	Component	Number of days monitored	Percentage sediment contribution, in terms of kg d^{-1}
6 (11.2.99-10.3.99)	Wash	27	Unknowns prevent calculations. But higher hillslope activity and fan erosion, suggest depositional channel activity. (See 4.2.2)
	Rockfall	27	
	Bank erosion	ND	
	Channel bed erosion	ND	
	Fan change	27	
13 (12.6.99-28.6.99)	Wash	16	2.97
	Rockfall	16	0.28
	Bank erosion	16	46.94
	Channel bed erosion	15	49.81 (Σ bank & channel = 96.75)
	Fan change	16	-
14 (28.6.99-12.7.99)	Wash	14	6.44
	Rockfall	14	1.04
	Bank erosion	ND	
	Channel bed erosion	13	Σ bank & channel = 92.52
	Fan change	14	-
21 (27.10.99-11.11.99)	Wash	15	0.23
	Rockfall	15	0.03
	Bank erosion	ND	
	Channel bed erosion	16	Σ bank & channel = 99.74
	Fan change	15	-
22 (11.11.99-4.12.99)	Wash	23	1.89
	Rockfall	23	0.92
	Bank erosion	27	66.95
	Channel bed erosion	25	30.24 (Σ B & C = 97.19)
	Fan change	25	-

Under all conditions the channel and banks are the most active and thus most important components of the system.

More detailed observations of the impact of meteorological conditions are provided on Figures 5.26-5.29, 5.31, and 5.33. These show the intra-zone variability of system components. Figure 5.26 views wash and rockfall yields in the primary zone. This clearly shows that under all conditions the gullies at the head of primary zone are more active than the lower right bank slope. In particular the central and left bank gullies are the most active. These locations have steeper slopes, and are dominated by better sorted granular material. The rockfall yields are limited to two sites, showing the lower one to be the more active, which is a reflection of the active rock face fracturing above the net. Figure 5.27 considers the same components as in Figure 5.26, but for the sub-primary zone. This is considerably less active than the primary zone, and reveals a weak seasonal sediment signal, with rockfall activity at a maximum in the summer.

Figure 5.28 shows the secondary zone, which shows strong seasonality in the wash activity, though the location of maximum yields varies between case studies. In the colder measurement intervals, the greater wash yields occur at higher elevations in the zone and vice versa during the summer (June-July 1999). This is probably a reflection of changing local sediment conditions. The upper Gerlach troughs are situated in localities where freeze thaw activity was greatest. The difference in altitude between the upper and lower troughs is small at 27 m (or c. 465 to 492 m O.D.) therefore a more likely explanation is the extent of exposure to sunlight. The lower Gerlach troughs are on open westerly slopes, whereas the upper troughs are on an enclosed north westerly slope. Therefore, microclimatic conditions may have an impact on ground temperatures. Furthermore, at the upper location the surface material was dominated by fractured bedrock, which is likely to release larger masses of material in the winter. In contrast the lower site was granular colluvium on a shallower slope. The greater summer yields on this colluvial material probably reflect a store of available material which was accessible to sheep, whereas the upper Gerlach trough slope retained little material after production, and the area was not crossed by sheep, hence the lower summer yields. The rockfall yields reveal little pattern.

Figure 5.26: Spatial variability of wash and rockfall yields in the primary zone in case study events

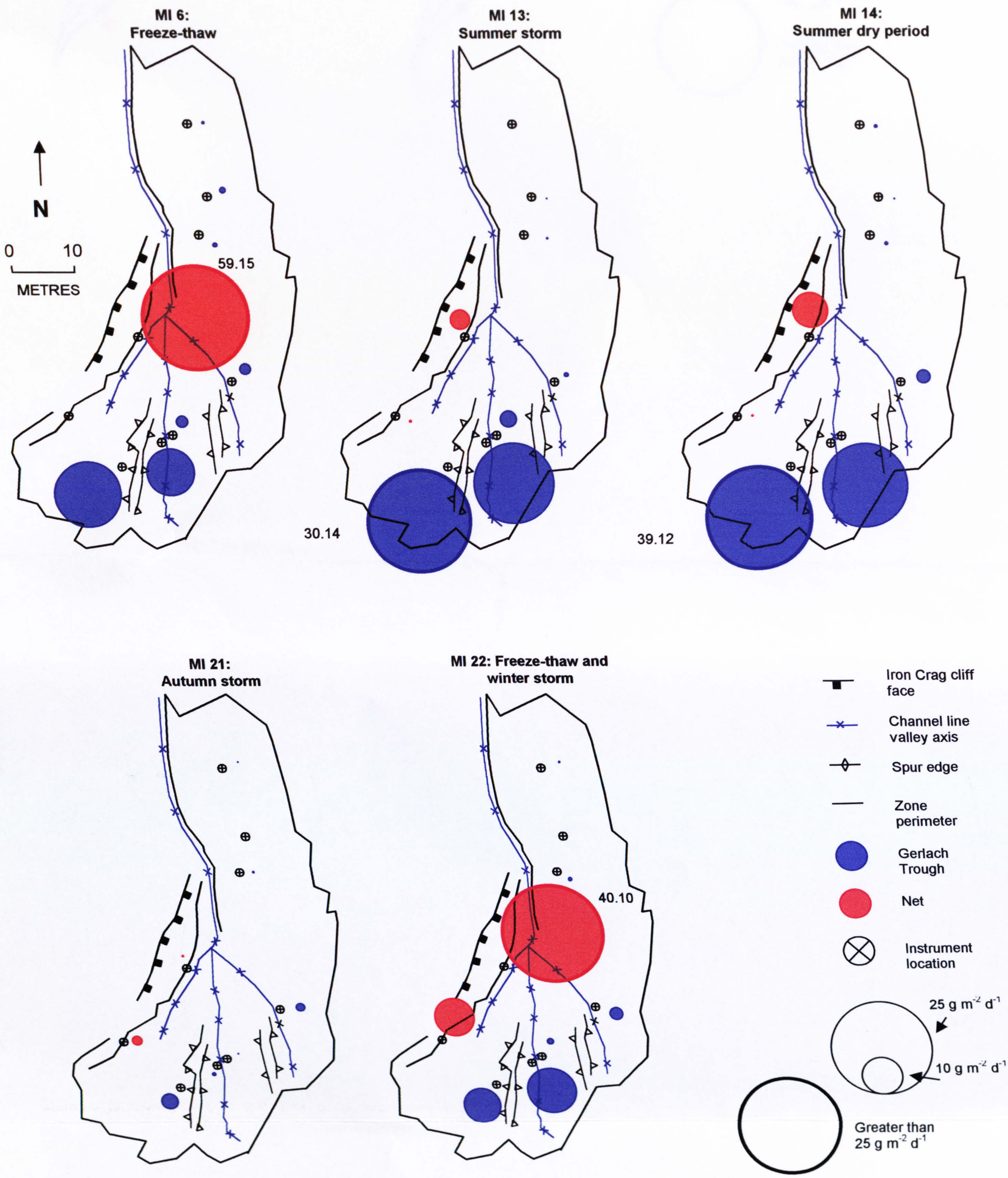


Figure 5.27: Spatial variability of wash and rockfall yields in the sub-primary zone in case study events

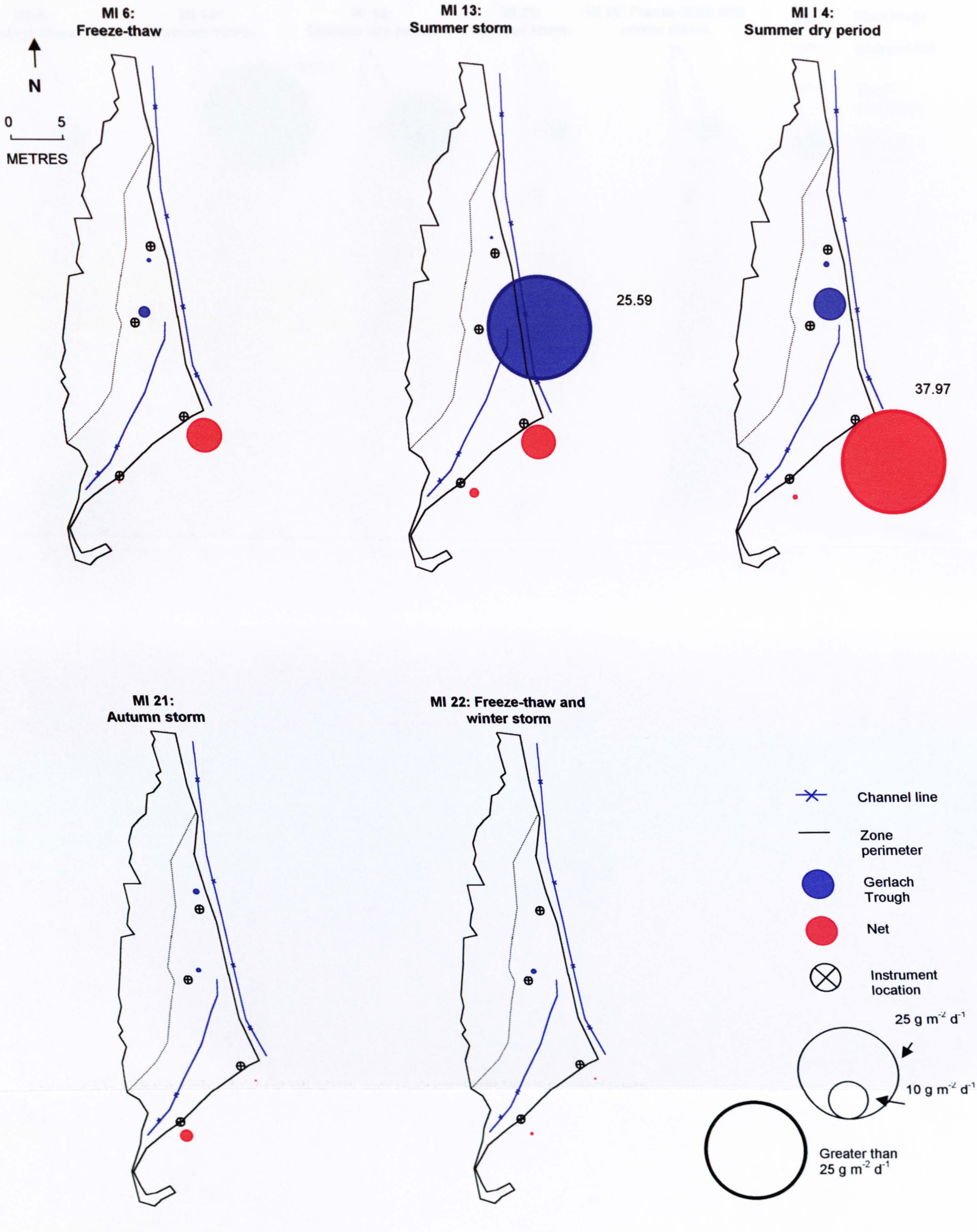


Figure 5.28: Spatial variability of wash and rockfall yields in the secondary and bedrock step zones in the case study event measurement intervals. N.B. 1. secondary rockfall yields use sub- primary surrogate so no instruments shown here; N.B. 2. rockfall in the bedrock step is shown adjacent to the upper left of the secondary zone.

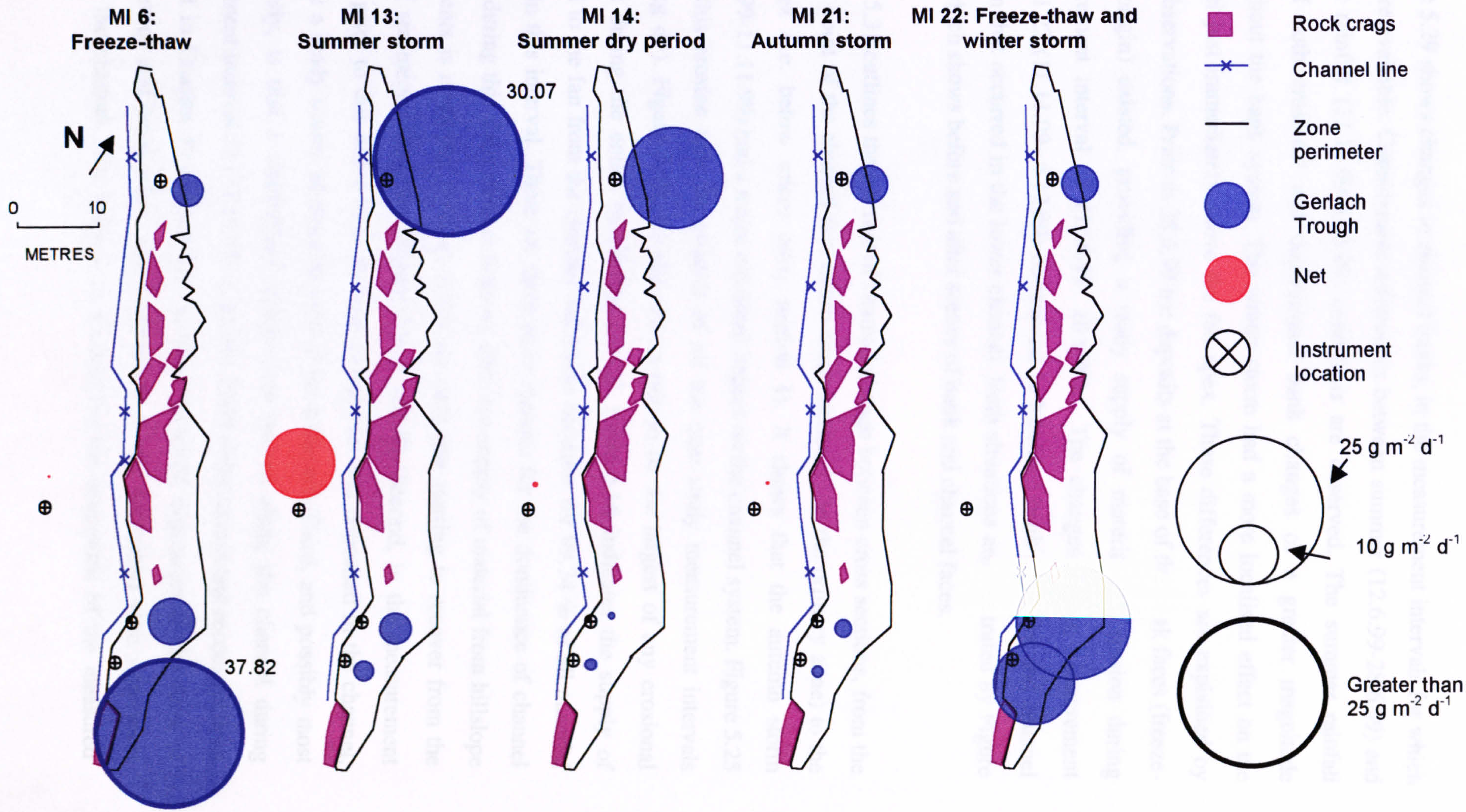


Figure 5.29 shows changes in channel banks, in the measurement intervals for which data are available. Considerable differences between summer (12.6.99-28.6.99) and winter rainfall (11.11.99-4.12.99) conditions are observed. The summer rainfall caused both erosional and depositional bank changes of a greater magnitude throughout the bank system. The winter storm had a more localised effect on the channel just immediately above the fan apex. These differences are explained by field observations. Prior to 28.6.99 toe deposits at the base of the bank faces (freeze-thaw origin) existed, providing a ready supply of material for erosion during measurement interval 13 (12.6.99- 28.6.99). The changes during measurement interval 22 (11.11.99- 4.12.99) correspond to localised bank collapses and channel incision that occurred in the lower channel. Both situations are illustrated by Figure 5.30, which shows before and after scenes of bank and channel faces.

Figure 5.31 outlines the net rate of channel change between cross sections, from the highest point of the channel (i.e. micro cross section 11 in the primary zone) to the fan apex (i.e. below micro cross section 1). It shows that the autumn storm (27.10.99-11.11.99) had a major erosional impact on the channel system. Figure 5.25 shows this erosion was the greatest of all the case study measurement intervals (2538 kg d^{-1}). Figure 5.10 (B) also shows this to be the largest of any erosional changes during the entire monitoring period. Table 5.16 indicates the supply of material to the fan from the channel and banks accounts for 99.74 % of all material supply in this interval. There are three main reasons for the dominance of channel erosion during this measurement interval. First the supply of material from hillslope components is relatively small as yields are only just starting to recover from the point of sediment exhaustion (Figure 5.9 A and B). Second, in the measurement interval prior to this one a large volume of material was deposited in the channel, therefore a ready source of material existed for transport. Third, and possibly most importantly, is that a channelised debris flow moved along the channel during measurement interval 21 (27.10.99-11.11.99). Field observations and reconstructions (reported in Chapter 8) showed this to cause localised deposition in the form of paired levees and basal lobes. More relevantly it was associated with significant scour of the channel, thus helping to account for the magnitude of the measured erosion.

Figure 5.29: Spatial variability of bank sedimentation along the channel, segregated into channel below bedrock step; and channel above bedrock step (micro cross section 8)

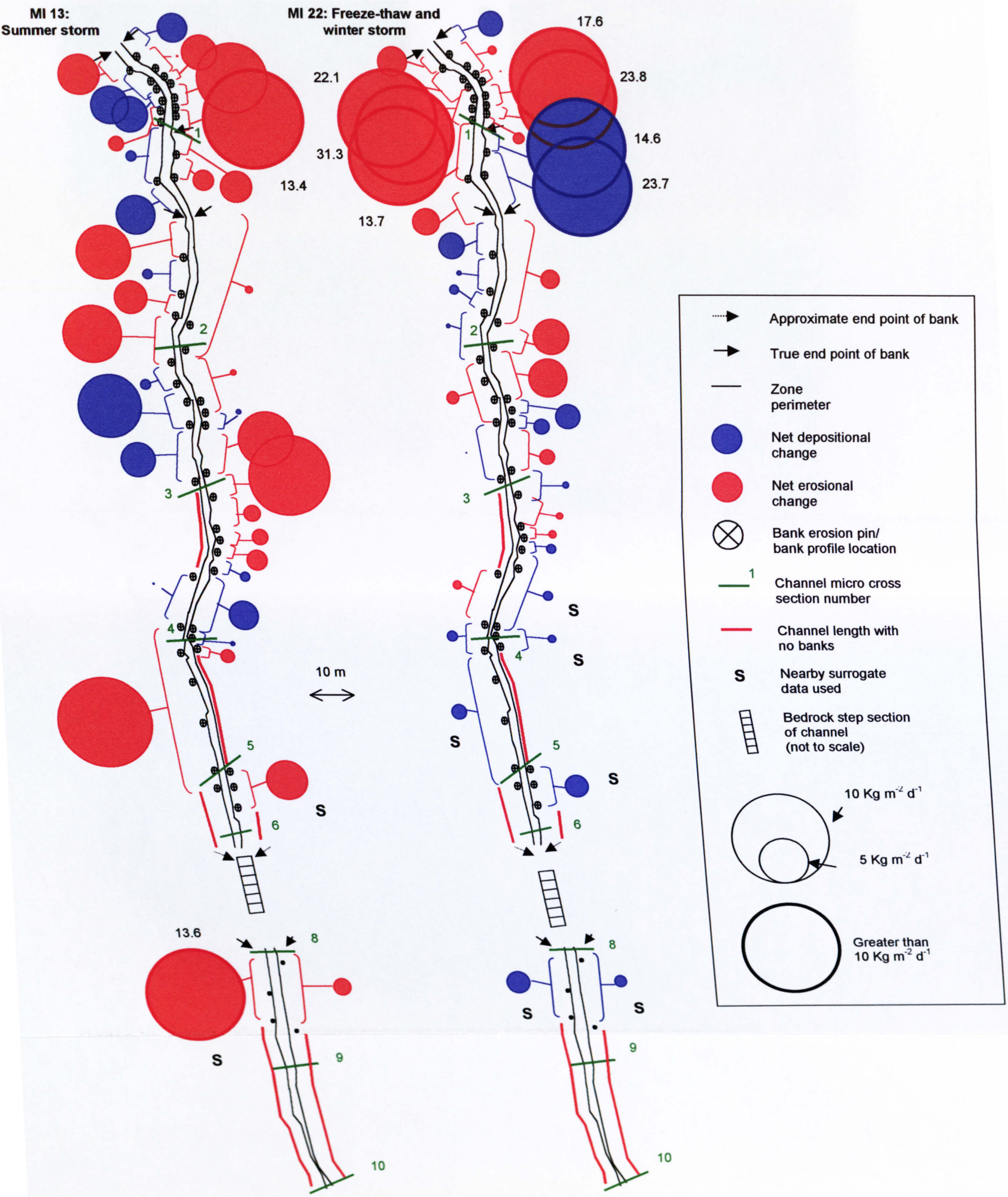


Figure 5.30: Photographs of the bank conditions, near the base of the channel/ fan system. (A) Example of freeze thaw toe deposit before MI 13. (B) Incised fan channel MI 22. (C) Incised fan channel following MI 22. (D) Enlargement of MI 22 impact on bank channel margin.

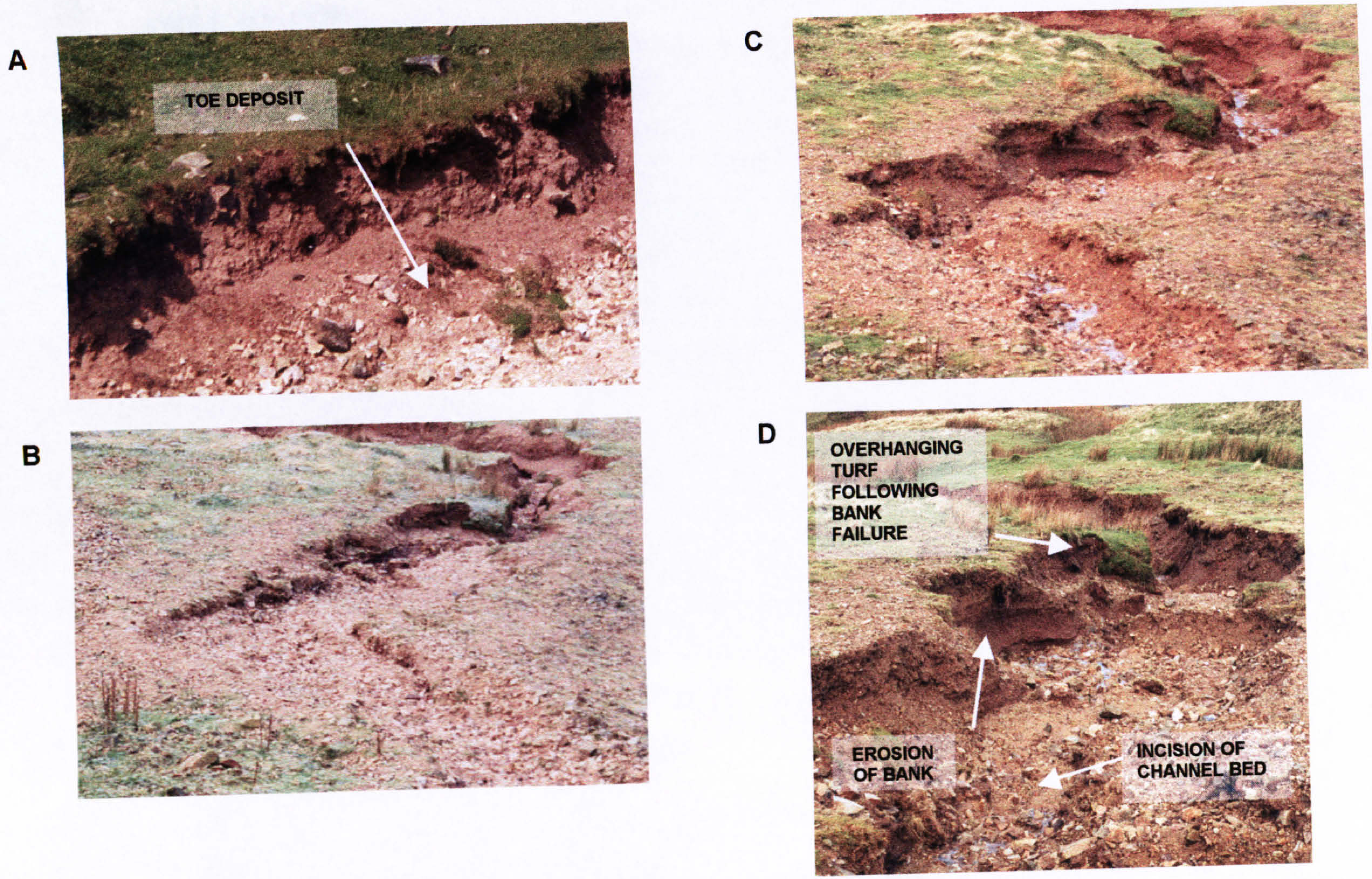
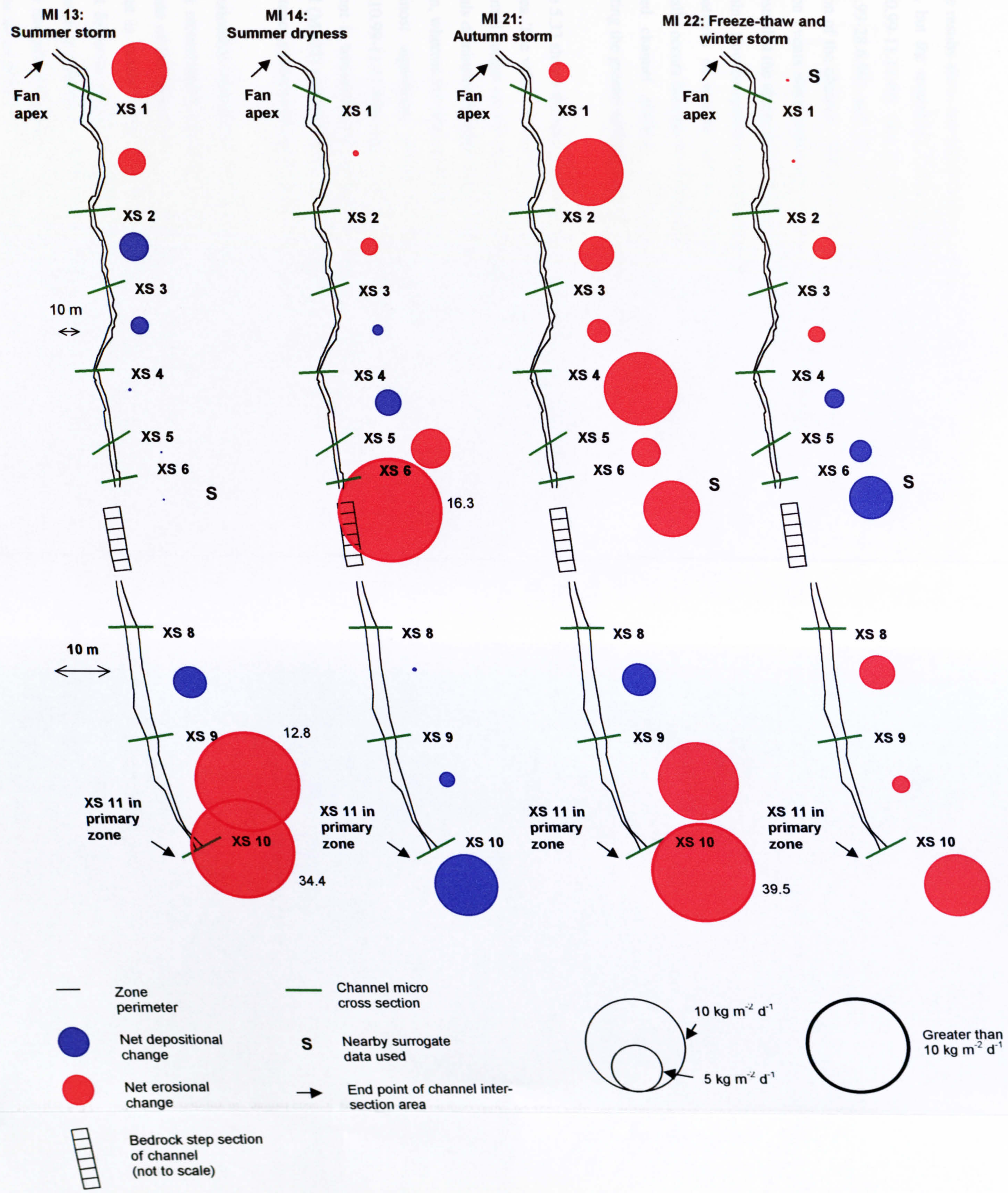


Figure 5.31: Spatial variability of channel change, segregated into channel below bedrock step; and channel above bedrock step (different scales).



These results show that rainfall can have a significant impact on the channel at Iron Crag, but the magnitude of the impact associated with measurement interval 21 (27.10.99-11.11.99) may be fairly unusual. Indeed in measurement intervals 13 (12.6.99-28.6.99) and 22 (11.11.99-4.12.99), large rain storms caused less net erosion of the channel, 1036 kg d^{-1} and 294 kg d^{-1} respectively. Also both of these erosion events show sequences of erosion and deposition along the channel. This suggests that the ability to transport sediment is erratic, and in areas of reduced slope declining flow competence results in the deposition of material. This would explain the patterns of erosion and deposition seen in Figure 5.31, where deposition generally occurs beneath the bedrock step, which Figure 5.32 shows to be a point of reduced channel gradient. Following deposition, erosion occurs downstream, reflecting the greater sediment transport capacity of the sediment-free flow.

Figure 5.33 shows the main peg array zones used in the calculation of net fan surface changes. The values shown are relevant to each of the zones, whereas the values in the annual budget are the sum of these changes. The Figure shows that measurement intervals dominated by rainfall show net deposition, which coincide with net channel erosion, whereas the other measurement intervals have net erosion of the fan surface. The most significant phases of fan deposition are measurement intervals 21(27.10.99-11.11.99); and 22 (11.11.99-4.12.99). In the first interval (MI 21) sediment is transported beyond the fan apex into new depositional lobes. In the second (MI 22) accumulation is greatest near the fan apex, possibly suggesting flow competence suddenly declines and sediment is rapidly deposited.

One noticeable anomaly in the relationship between the channel and fan process rates is measurement interval 22 (11.11.99-4.12.99). This interval has the highest daily rate of fan deposition, yet a small rate of channel erosion. It is possible that sediment is eroded from the channel and banks just above the fan. This would account for some of the imbalance here and in the annual sediment budget. This could arise if significant change occurred between micro cross sections and bank profiles and not at the measurement points, then the volume of sediment calculated would be an underestimation. In retrospect the only way to minimise this occurrence is to increase the number of cross sections.

Figure 5.32: Long profile of the Iron Crag torrent system, from the head of the system down to the fan

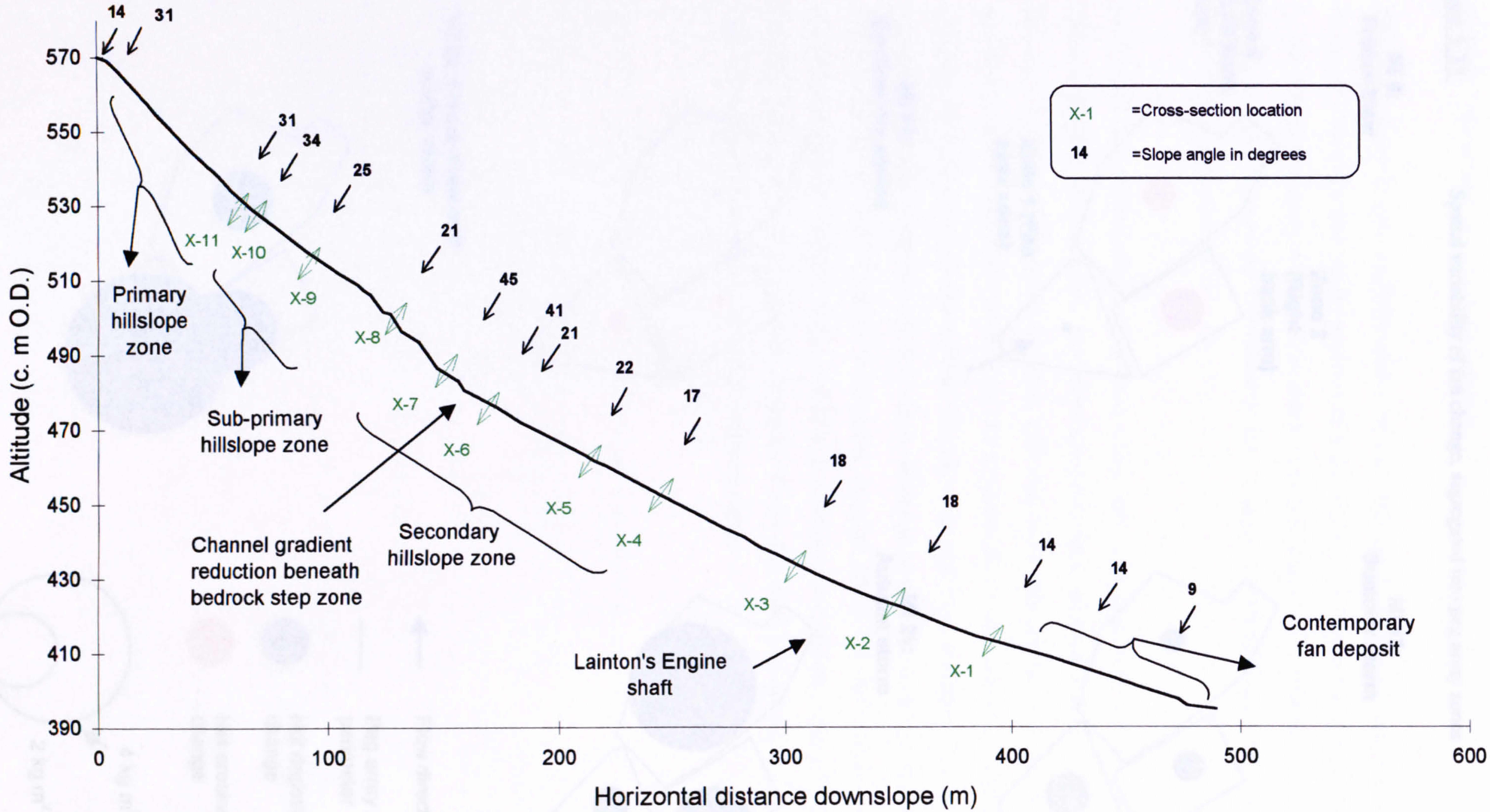
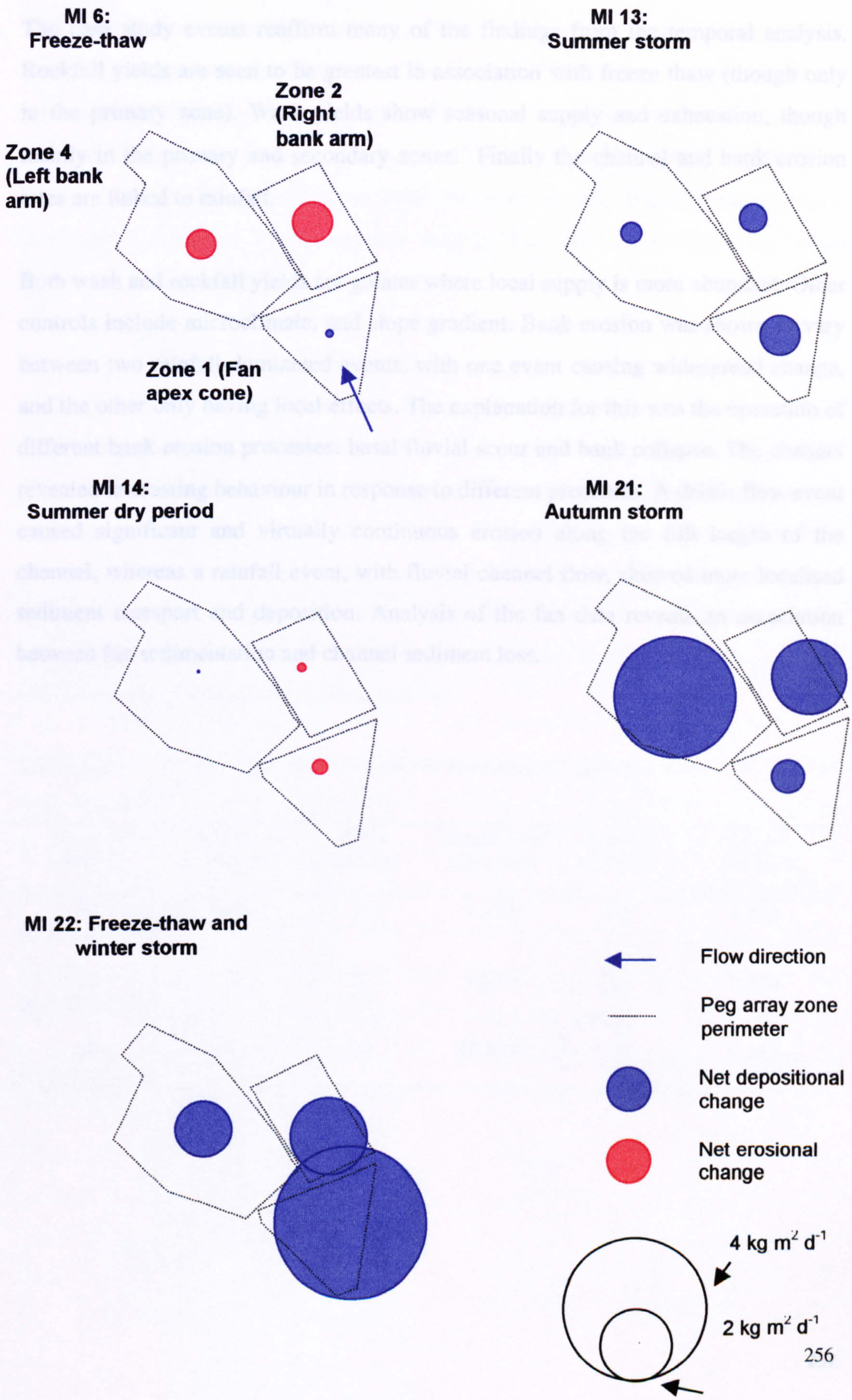


Figure 5.33: Spatial variability of fan change, segregated into peg array zones



5.2.3.4 Summary of case study impacts

The case study events reaffirm many of the findings from the temporal analysis. Rockfall yields are seen to be greatest in association with freeze thaw (though only in the primary zone). Wash yields show seasonal supply and exhaustion, though mainly in the primary and secondary zones. Finally the channel and bank erosion rates are linked to rainfall.

Both wash and rockfall yields are greater where local supply is more abundant. Other controls include microclimate, and slope gradient. Bank erosion was shown to vary between two rainfall-dominated events, with one event causing widespread change, and the other only having local effects. The explanation for this was the operation of different bank erosion processes: basal fluvial scour and bank collapse. The channel revealed interesting behaviour in response to different processes. A debris flow event caused significant and virtually continuous erosion along the full length of the channel, whereas a rainfall event, with fluvial channel flow, showed more localised sediment transport and deposition. Analysis of the fan data reveals an association between fan sedimentation and channel sediment loss.

5.3 Ancillary measurements: bedload tracer

Bedload tracer clasts provide a further measure of channel change. At three sites 50 magnetic tracers were introduced into the channel. These were immediately below cross section 10 (Series 1- S1), cross section 8 (Series 2- S2), and just upstream of cross section 2 (Series 3- S3) (see Figure 5.32). The tracer clasts were sampled from local material at these sites in June 1998. Material was dug from the bed *en masse* and bagged to collect a representative sample. This material was returned to the laboratory where clasts large enough to contain a magnet (b axis > 50 mm) were drilled; magnets inserted and sealed with silicon sealant. Clast were painted and labeled, and finally measurements of tracer size, mass, and corner roundness were made. Tables 5.17 and 5.18 outline details of the bed material tracers and their installation sites. Figure 5.34 shows each of the tracer sites just after installation. Where possible, tracer was laid in the surrounding bed material to provide similar packing characteristics. In the case of the S 1 and S 2 tracer groups, bedrock prevented this. Figure 5.34 also shows that finer material was painted and reintroduced. This disappeared very quickly and was rarely seen again, although importantly a few fine fragments of all tracer series were located on the fan, showing effective connectivity of the channel and fan.

Table 5.17: Details of bed material tracers and installation site characteristics

Site and altitude	Colour of tracer	Total number	Experiment start date	Channel width (m)	Local channel slope (m m^{-1})
S1 (c. 525 m O.D.)	Yellow	50	4.9.98	1.6	0.466
S2 (c. 500 m O.D.)	Red	50	4.9.98	2.6	0.762
S3 (c. 425 m O.D.)	Blue	50	30.8.98	1.7	0.243

Table 5.18: Tracer clast summary statistics

Tracer statistics	Series 1	Series 2	Series 3
SIZE (b-axis) (mm)			
Maximum	146	148	167
Minimum	54	50	52
Mean	94	89	96
Standard deviation	25.55	25.28	23.44
MASS (g)			
Maximum	2507	2015	1966
Minimum	167	145	173
Mean	803	749	861
Standard deviation	544.29	504.31	424.76
ROUNDNESS (cm)			
Maximum	1	0.8	1.5
Minimum	0.1	0.1	0.2
Mean	0.44	0.42	0.45
Standard deviation	0.19	0.13	0.21

Tracers were resurveyed at quarterly measurement intervals or following significant storm events. The first movement of the tracer occurred on the 10.10.98 in association with a period of intense rainfall, peaking at an hourly intensity of 11.2 mm. As the tracer had just been installed it was less stable than the surrounding bed material and thus prone to movement (particularly sites S1 and S2). Field observation indicates that rainstorms between 8-10.10.98 had a significant geomorphological impact on the system including local incision and deposition in the channel, bank collapses and fresh fan deposits. Subsequent measurements of tracer were made on 19.12.98 (start of sediment budget monitoring), 25.3.99, 14.6.99, 22.9.99, 13.11.99, and 3.1.00 (post sediment budget) (see Table 5.19). The recovery of tracers are outlined by Table 5.19 showing a maximum of 73 % and at worst 58% for all the tracers installed. The amount of recovery was greatest on the survey of 14.6.99, but declined thereafter.

Figure 5.34: Photographs of tracer installation at each series start line, August-September 1998. (A) Series 1 tracer clasts and fines; (B) Series 2 tracer clasts and fines, (C) Trench dug in channel bed for Series 3 tracer clasts; and (D) Series 3 tracer clasts and fines after insertion.

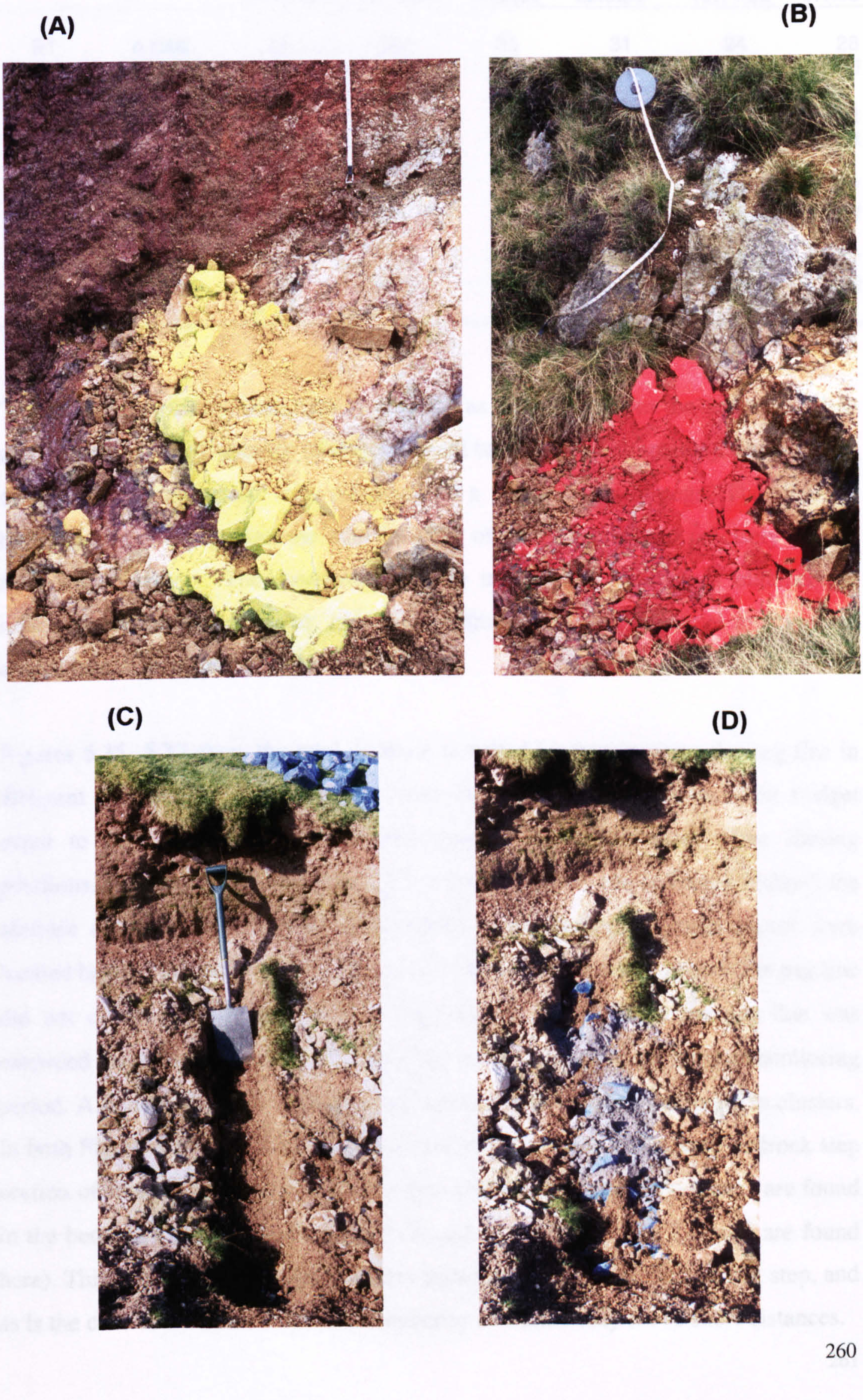


Table 5.19: Recovery of tracers

Series	Info	Install-19.12.98	19.12.98-25.3.99	25.3.99-14.6.99	14.6.99-22.9.99	22.9.99-13.11.99	13.11.99-3.1.00
S1	n total	31	29	35	31	24	28
	% total	*62*	*58*	*70*	*62*	*48*	*56*
S2	n total	37	42	43	39	32	32
	% total	*74*	*84*	*86*	*78*	*64*	*64*
S3	n total	31	30	32	28	32	27
	% total	*62*	*60*	*64*	*56*	*64*	*54*
All	n total	99	101	110	98	88	87
	% total	*66*	*67.3*	*73.3*	*65.3*	*58.6*	*58*

The results that follow report tracer location as a distance from the series start line and as a mean travel distance (distance moved between measurements). The distance downstream is measured with reference to a series of bank pegs. The distance between all bank pegs and the start location of tracer are known precisely from a total station survey. The measurement of a tracer clast location is obtained by intersection from known bank pegs, with adjustments for horizontal and vertical angles (see Appendix 5.1: 14 for more detail).

Figures 5.35- 5.37 show the total distance travelled by tracers along the peg line in different measurement intervals. All these Figures show the pre-sediment budget event to have caused significant movement of the tracer away from starting positions. Further to this in Figure 5.37 (survey 19.9.98- pre sediment budget) the absence of tracers beyond the main channel is misleading, as some tracers were located beyond this point (n=10). They were not measured at this time as the peg line did not extend beyond this point. In response to this omission the peg line was extended for subsequent surveys conducted during the sediment budget monitoring period. A noticeable trend throughout all surveys is that tracers are found in clusters. In both Figures 5.35 and 5.36 clusters of tracer occur beneath the steep bedrock step section of channel, an area of sediment deposition, whilst very few tracers are found in the bedrock step section of channel (though more from series 2 than 1 are found here). This is because the series 2 tracers start just upstream of the bedrock step, and as is the case with all tracer series the majority of tracers only move short distances.

Figure 5.35: Location of series 1 tracers after each survey

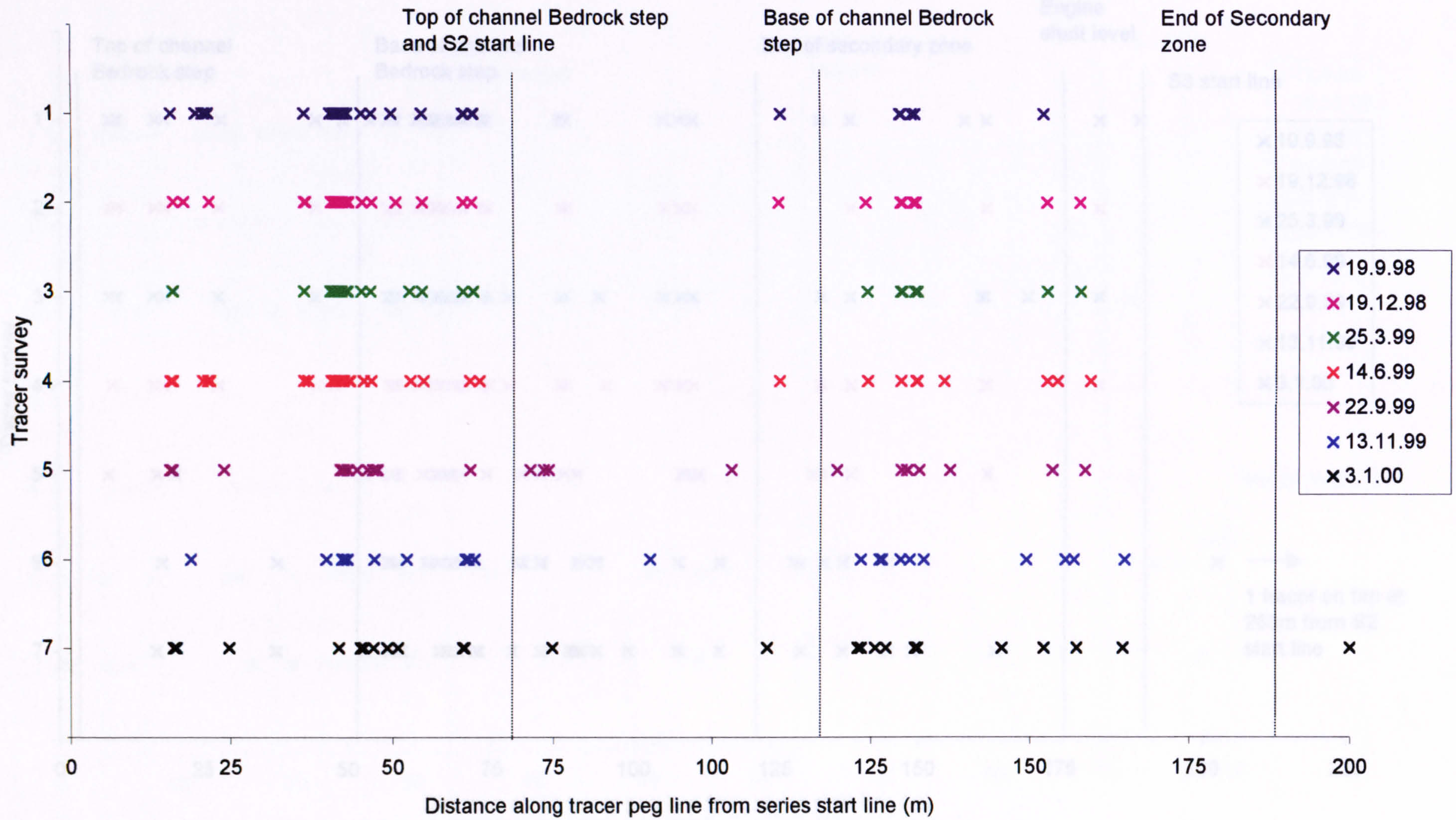


Figure 5.36: Location of series 2 tracers after each survey

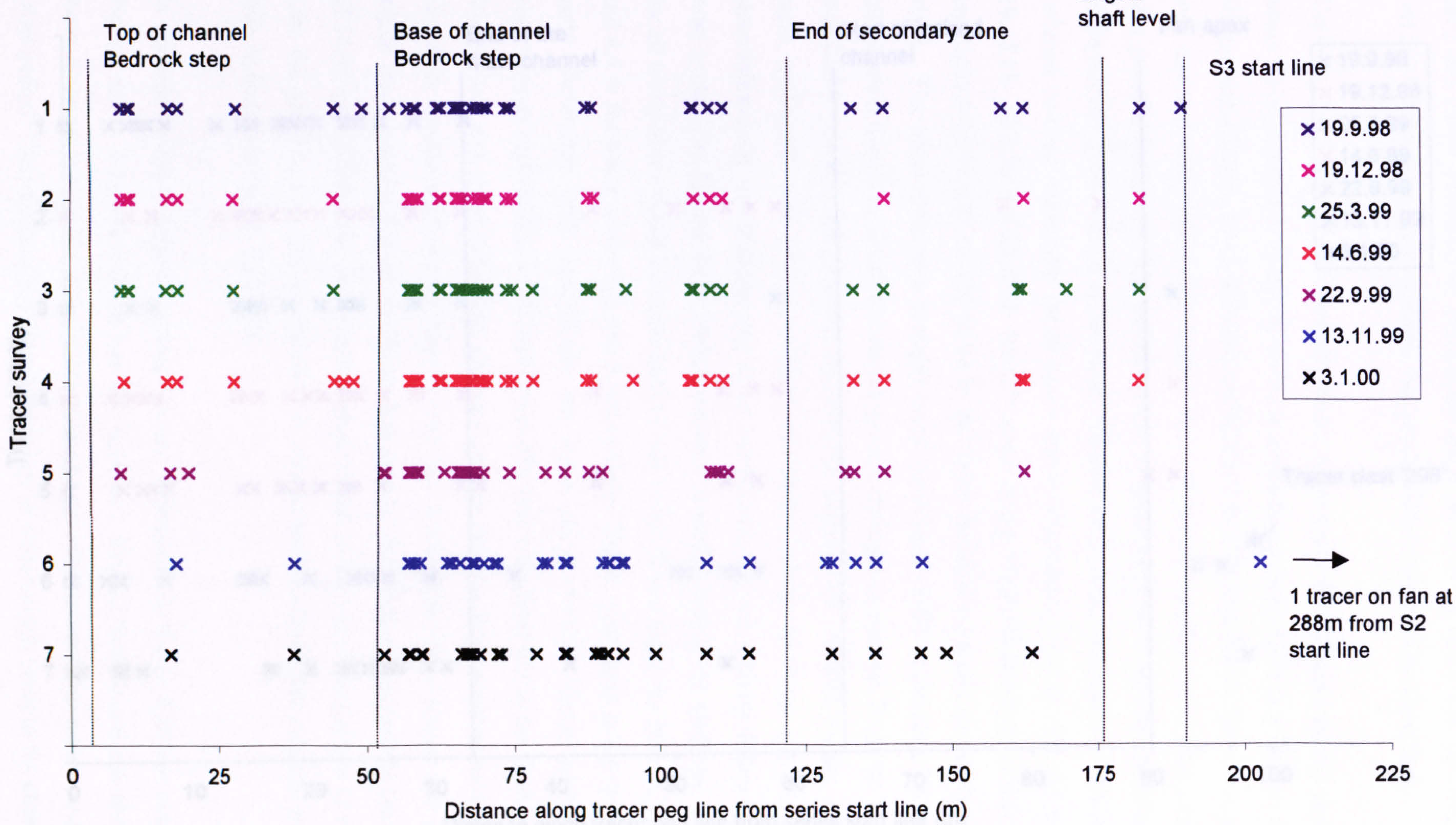
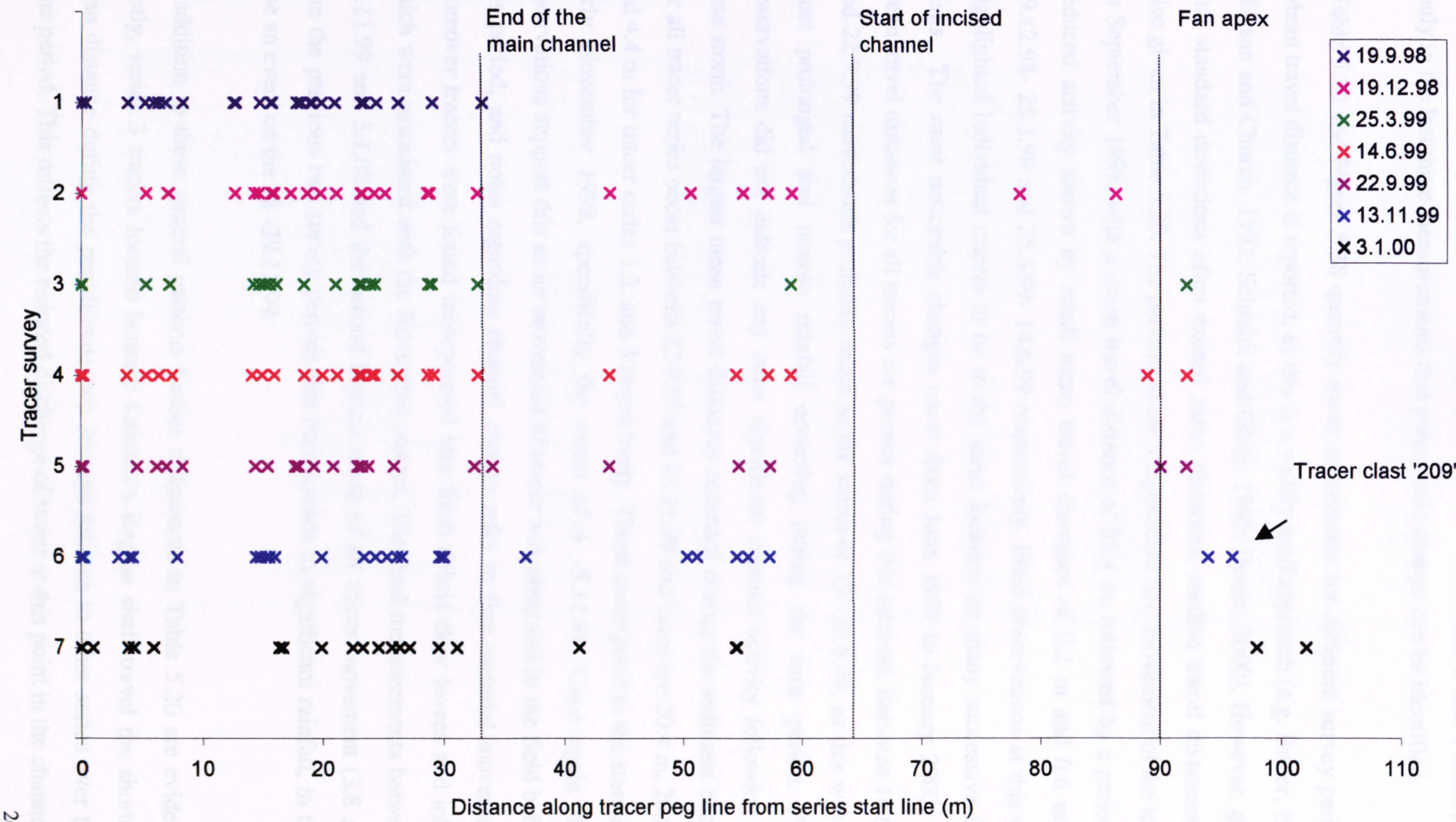


Figure 5.37: Location of series 3 tracer after each survey



As expected the number of tracers declines with distance from the starting line. It is seen that tracer distributions are largely static between 19.12.98 and 14.6.99, it is only in the last three measurements that perceptible change can be identified.

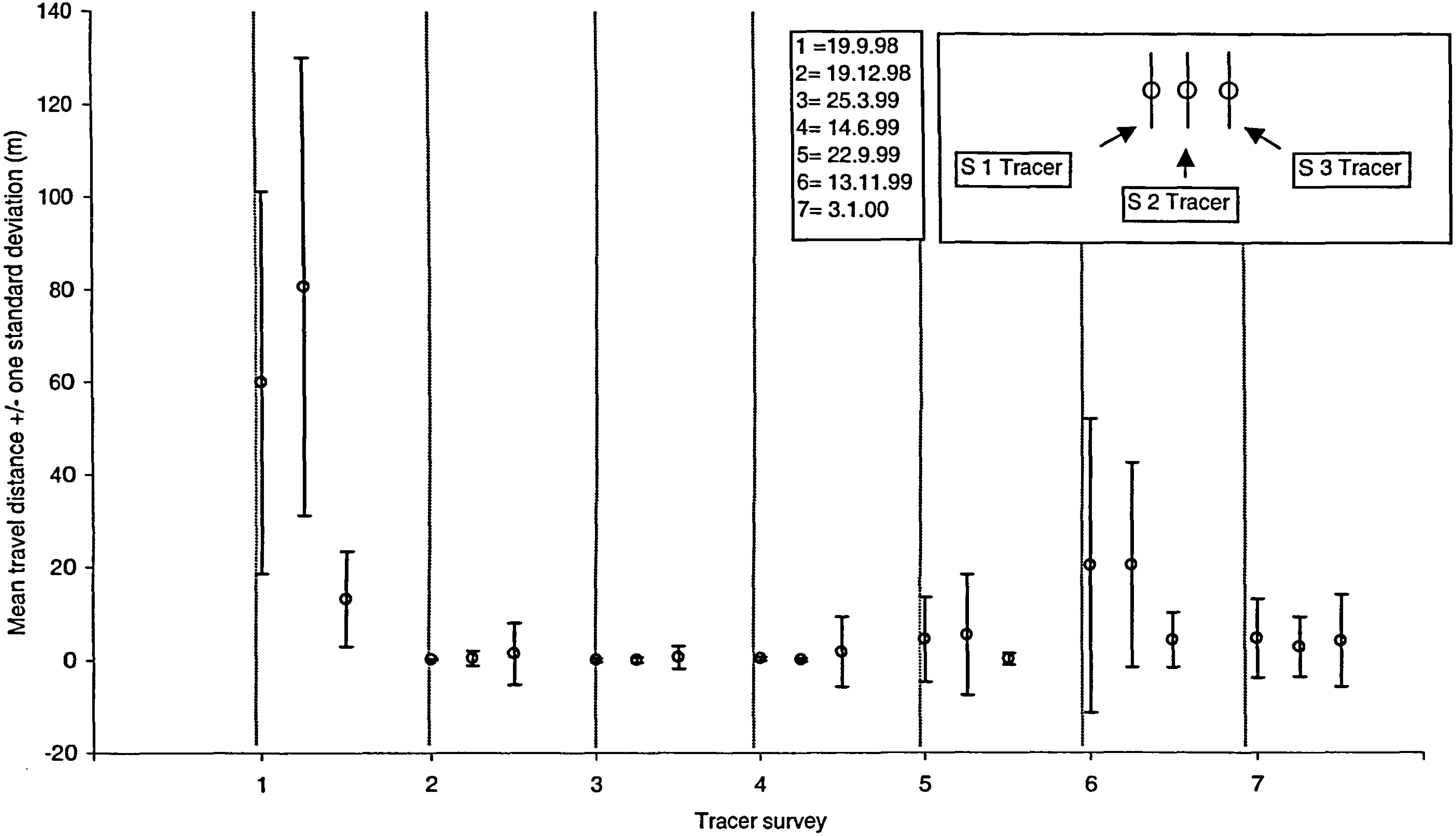
Table 5.20 and Figure 5.38 quantify tracer movements for different survey periods. Mean travel distance is reported, as this is a widely used approach (e.g. Butler, 1977; Hassan and Church, 1992; Schmidt and Gintz, 1995; Demir, 2000). However, given that standard deviations often exceed mean distances, median travel distances are also given in Table 5.20. The patterns show a significant first movement of the tracer in September 1998, with a mean travel distance of 55.4 m, followed by a period of reduced activity shown by small mean travel distances of 0.2 m and 0.6 m for 19.12.98- 25.3.99 and 25.3.99- 14.6.99 respectively. Field observations at this time highlighted individual tracers to be in the same location on many successive field visits. The most noticeable changes occur from June 1999 to January 2000. The mean travel distances for all tracers are greater during this interval. Between 14.6.99 and 22.9.99 movements probably relate to the storm of 19 -20.6.99, as this was the most prolonged and intense rainfall occurring during the time period. Field observations did not indicate any other significant channel activity following the June storm. The largest mean travel distances recorded during the sediment budget for all tracer series occur between 22.9.99 and 13.11.99 and these are 20.4 m, 20.5m, and 4.4 m for tracer series 1,2, and 3 respectively. These correspond to the storms of early November 1999, specifically the event of 4 -5.11.99. Once again field observations support this as no movement of tracer was observed in the field before this period, and notes regarding channel change refer to fine material movement. Moreover tracers were found incorporated into fresh debris flow levees and lobes which were associated with the November storms. The final measurements between 13.11.99 and 3.1.00 had the second highest mean of all tracer movement (3.8 m). Like the previous two survey periods this corresponds to significant rainfall, in this case an event on the 28 -29.11.99.

In addition to these general patterns further differences in Table 5.20 are evident. Firstly, series 3 tracers located beneath Lainton's Engine shaft travel the shortest mean distance during the penultimate two surveys relative to other series over the same period. This reflects the reduced discharge of water at this point in the channel,

Table 5.20: Travel distances of tracers in metres

Series	Info.	Install-19.9.98	19.9.98-19.12.98	19.12.98-25.3.99	25.3.99-14.6.99	14.6.99-22.9.99	22.9.99-13.11.99	13.11.99-3.1.00
ALL	Maximum	215.46	30.79	10.46	37.01	61.65	112.78	46.73
	Mean	**55.41**	**0.60**	**0.18**	**0.60**	**3.62**	**15.36**	**3.83**
	Median	42.06	0.07	0.00	0.13	0.72	4.59	0.39
	Standard deviation	48.02	3.64	1.25	3.90	9.82	23.18	8.29
S1	Maximum	158.94	0.70	2.04	1.52	39.63	112.78	32.89
	Mean	**59.89**	**0.14**	**0.02**	**0.34**	**4.43**	**20.42**	**4.73**
	Median	42.18	0.09	0.00	0.23	1.05	4.60	**2.08**
	Standard deviation	41.21	0.17	0.43	0.41	9.14	31.70	8.51
S2	Maximum	215.46	8.38	2.69	1.18	61.65	69.41	21.35
	Mean	**80.51**	**0.41**	**0.08**	**0.06**	**5.43**	**20.49**	**2.85**
	Median	67.54	0.05	0.00	0.03	0.67	12.56	0.04
	Standard deviation	49.39	1.59	0.55	0.29	13.01	22.02	6.45
S3	Maximum	33.02	30.79	10.46	37.01	5.40	18.14	46.73
	Mean	**13.25**	**1.36**	**0.58**	**1.80**	**0.28**	**4.36**	**4.15**
	Median	14.73	0.00	0.00	0.11	0.00	0.71	0.56
	Standard deviation	10.20	6.59	2.41	7.55	1.22	5.90	9.91

Figure 5.38: Travel distances for each tracer series in each tracer survey



as some water infiltrates the channel bed prior to this point. This is most evident during the summer when the lower channel was often dry. Secondly, between 19.12.98- 14.6.99, the series 3 tracer has the greatest mean and maximum travel distances of all tracers, which may correspond to the freezing over and snow cover of the upper parts of the channel during the winter months. Thus flow duration may be greater in the lower channel which experiences less freezing, and also receives the melt water from higher in the channel and adjacent slopes. Thirdly, between 22.9.99- 13.11.99 the mean travel distances are similar for tracer series 1 and 2, but dramatically less for series 3. In addition to the declining flow downstream, field observation identified evidence of debris flow activity above the bedrock step until cross section 4. This specified channel reach corresponds to the siting of series 1 and 2 tracer, but not 3. Coarse sediment movement as a debris flow 'slug' would tend to produce locally high tracer displacements.

So far the analysis of tracer transport distances has confirmed previous findings with regard to the channel. As stated in section 5.2.2, channel erosion coincides with periods of increased rainfall. Second as shown in section 5.2.3.3 the rainfall- debris flow event, occurring in measurement interval 21 (27.10.99- 11.11.99), produced the greatest channel change in the entire sediment budget monitoring period. Also when tracer clasts are generally static the channel still yields sediment to the fan, thus implying that the sediment transported is finer material than the tracer-sized material. To seek a more detailed understanding of coarse sediment transport in the Iron Crag channel, analyses of travel distance versus both tracer size and shape are performed. These variables have been shown to represent some of the particle characteristics considered to influence the movement of bedload (Hassan and Church, 1990; Ferguson and Ashworth, 1992; Demir, 2000). Analyses are performed with the travel distance data from measurements between 14.6.99- 22.9.99, 22.9.99- 13.11.99; and 13.11.99 to 3.1.00, as these have previously been shown to be the most active phases of tracer transport, and thus more likely to show variation. Figures 5.39-5.41 show relationships between travel distance and particle size, according to measurement interval and tracer series. In Figures 5.39 and 5.40 the overall trends are for smaller sized particles to travel further, though the relationships are generally insignificant having very weak R^2 values between 0.0053 ($p< 0.719$) and 0.1676 ($p <0.073$). S2 tracers show the weakest relationships. Indeed, S2 tracer between 22.9.99 and

13.11.99 (Figure 5.40-B), shows the most insignificant relationship clearly suggesting travel distance is here independent of size. This probably reflects the occurrence of the debris flow at this locality, as it is known that debris flows tend to move material *en masse* (for example Costa, 1988; Davis, 1992; Coussot and Meunier, 1996). Figure 5.41 shows the relationships between 13.11.99 and 3.1.00 to be more varied than previous survey periods. Series 1 tracer travel distances correlate positively with clast size, whilst two and three are negative, and once more all are statistically insignificant. The relationships between distance and size collectively tend to suggest some relationship between the two variables in the direction expected, i.e. smaller clasts travel further, though the statistical insignificance of the relationships indicates other variables to have a great influence on particle transport. A more plausible finding is that debris flow activity transports all sediment irrespective of size. Also in very steep channels the threshold of entrainment for a range of bed material sizes can be very narrow and patterns of dispersal (sorting) are strongly influenced by local bed topography.

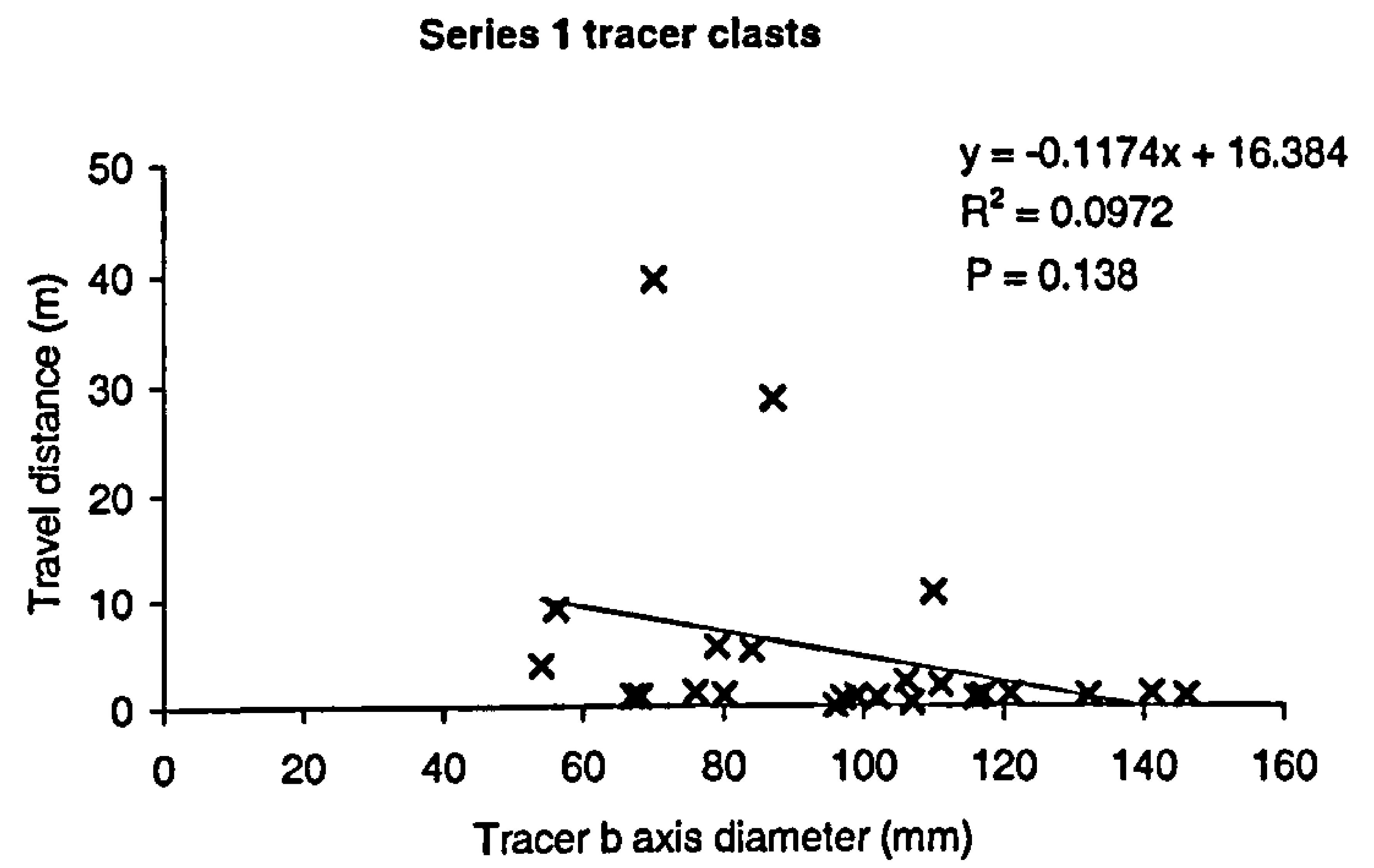
Table 5.21 and Figure 5.42 classify all series tracer clasts according to Zingg shape, and largely shows rod and sphere shaped particles to be transported greater mean distances than blades and discs. Between 22.9.99- 13.11.99 rods are transported the greatest distance, though in the fluvial survey periods it is spheres which are transported a greater distance. Also between September and November 1999 discs show the lowest mean distance travelled, but in the previous fluvial period blade shaped particles are transported the shortest distance. An exception to these rules is the transport of blades between 13.11.99 and 3.1.00. In this period blades have the highest mean travel distance (6.9 m). However this high value is the consequence of a single clast that was transported nearly 47 m, removing this value reduces the mean distance to 1.3 m, the standard deviation to 2.65, and the median to 0.46 m.

Hence the finding that spheres and rods travel greater distances confirms the findings of Demir (2000, p234) who with regard to natural tracer movements states:

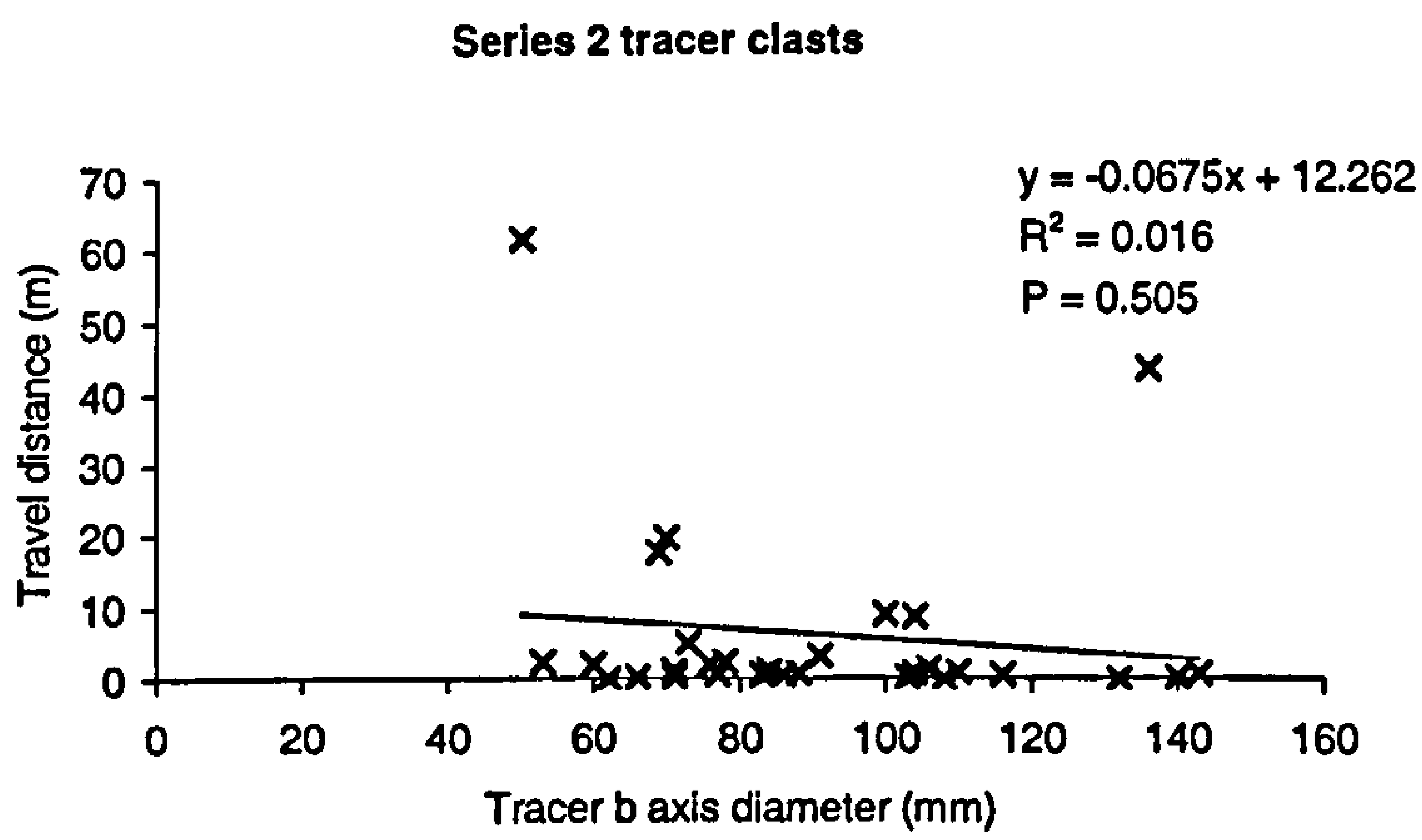
"The reason why the spheres and to some extent rods have longer mean transport distances, but disc and blades do not, may be that, because spheres and rods are largely rolled rather than lifted..."

Figure 5.39: Relationship between travel distance and particle size between 14.6.99 and 22.9.99

(A)



(B)



(C)

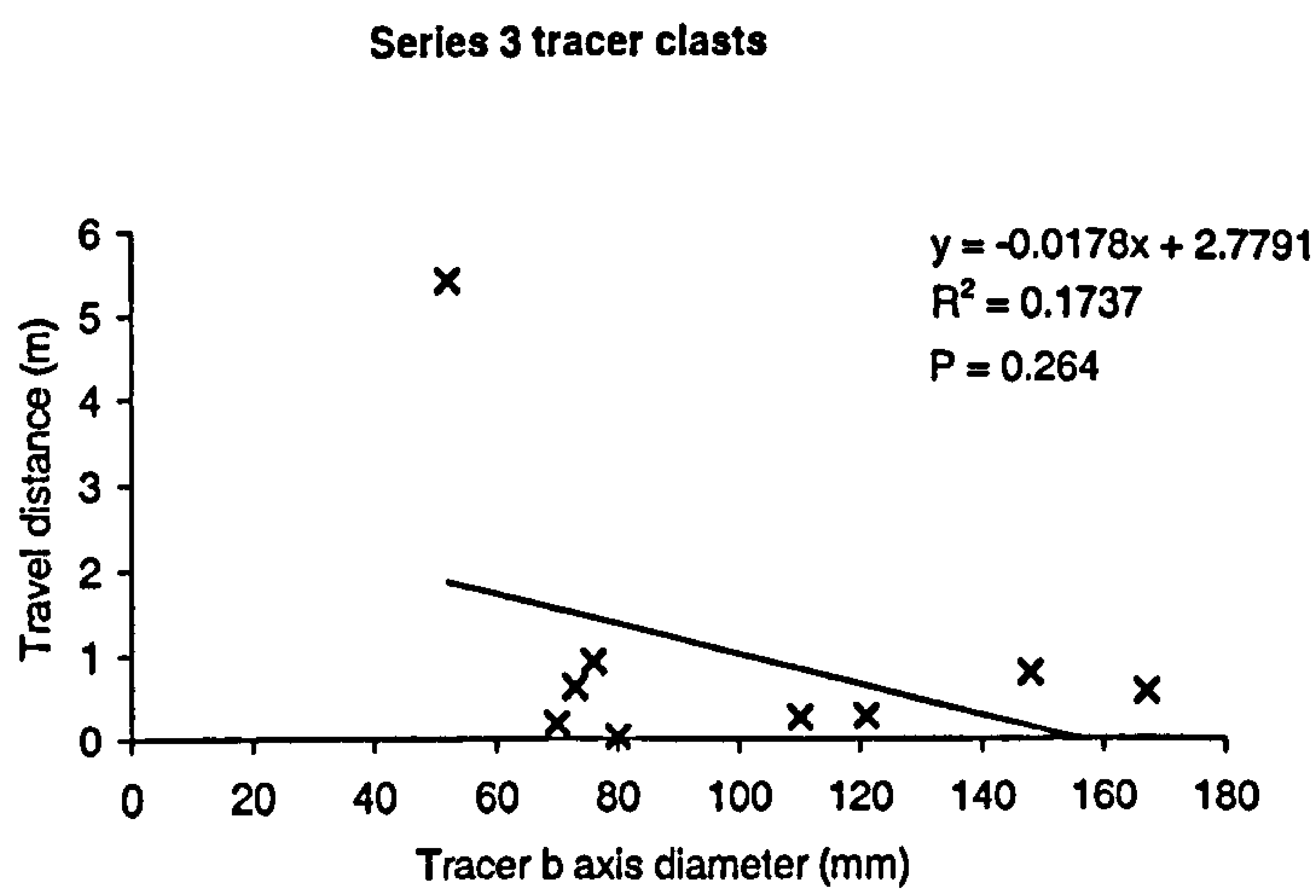
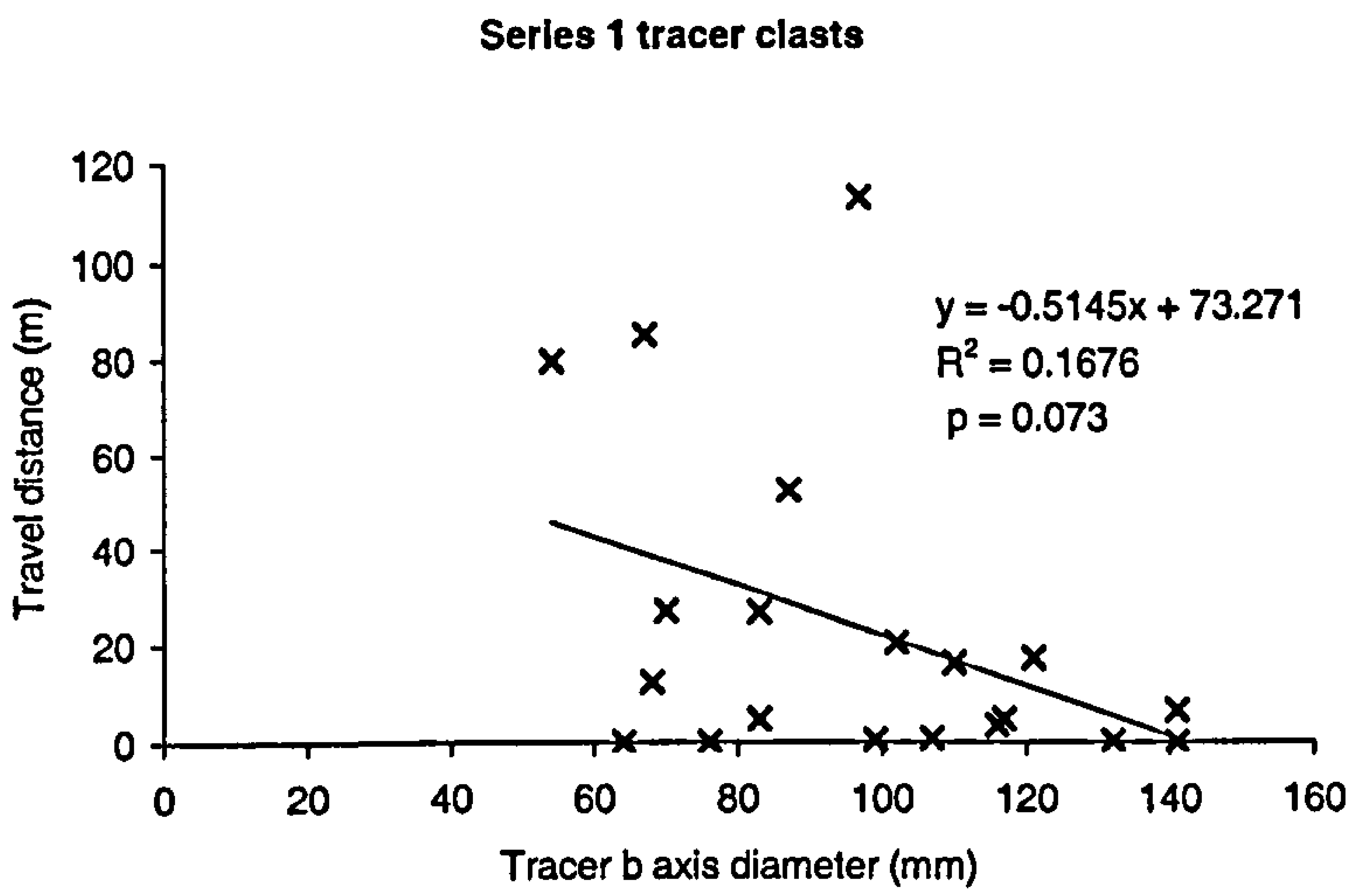
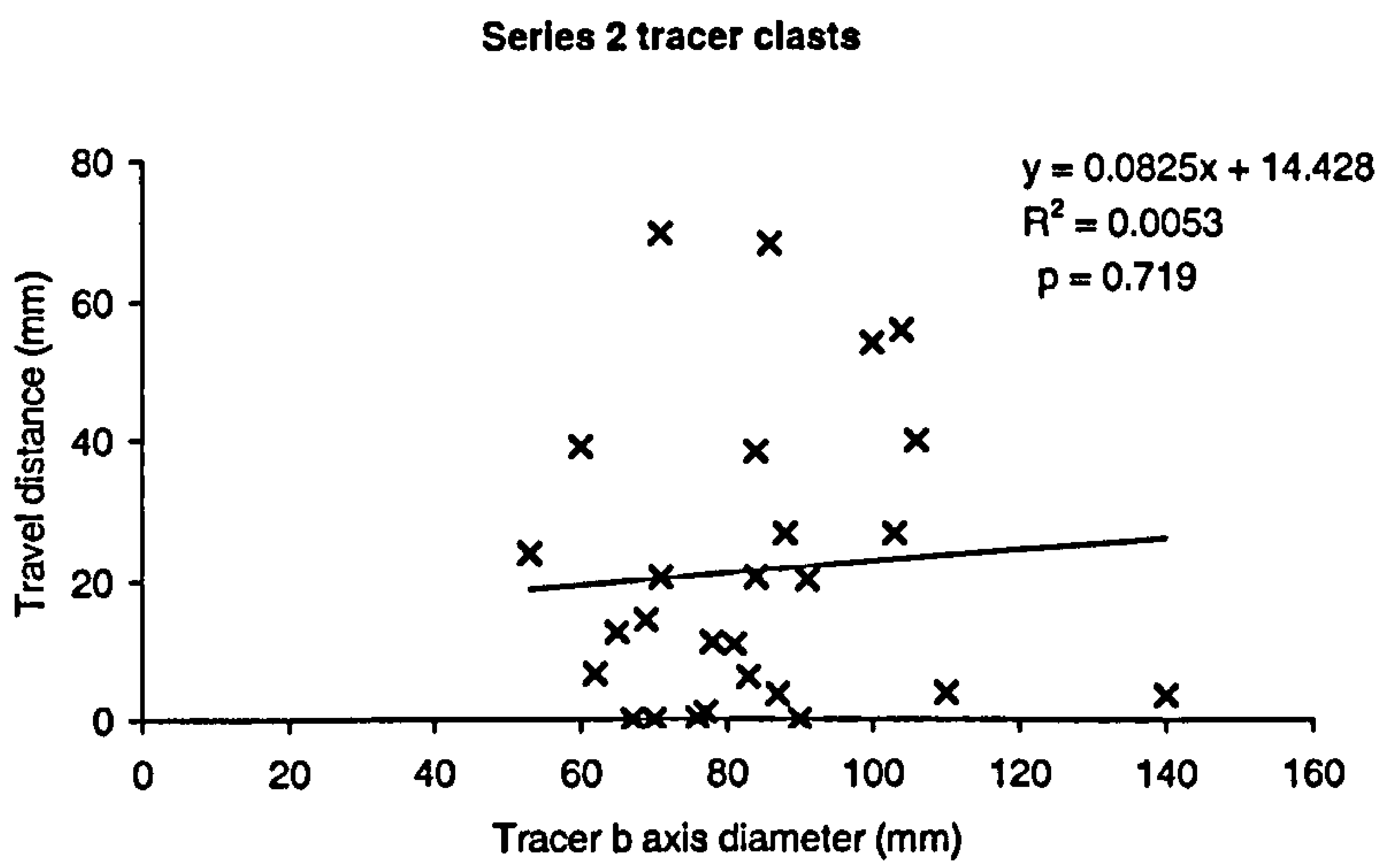


Figure 5.40: Relationship between travel distance and particle size between 22.9.99 and 13.11.99

(A)



(B)



(C)

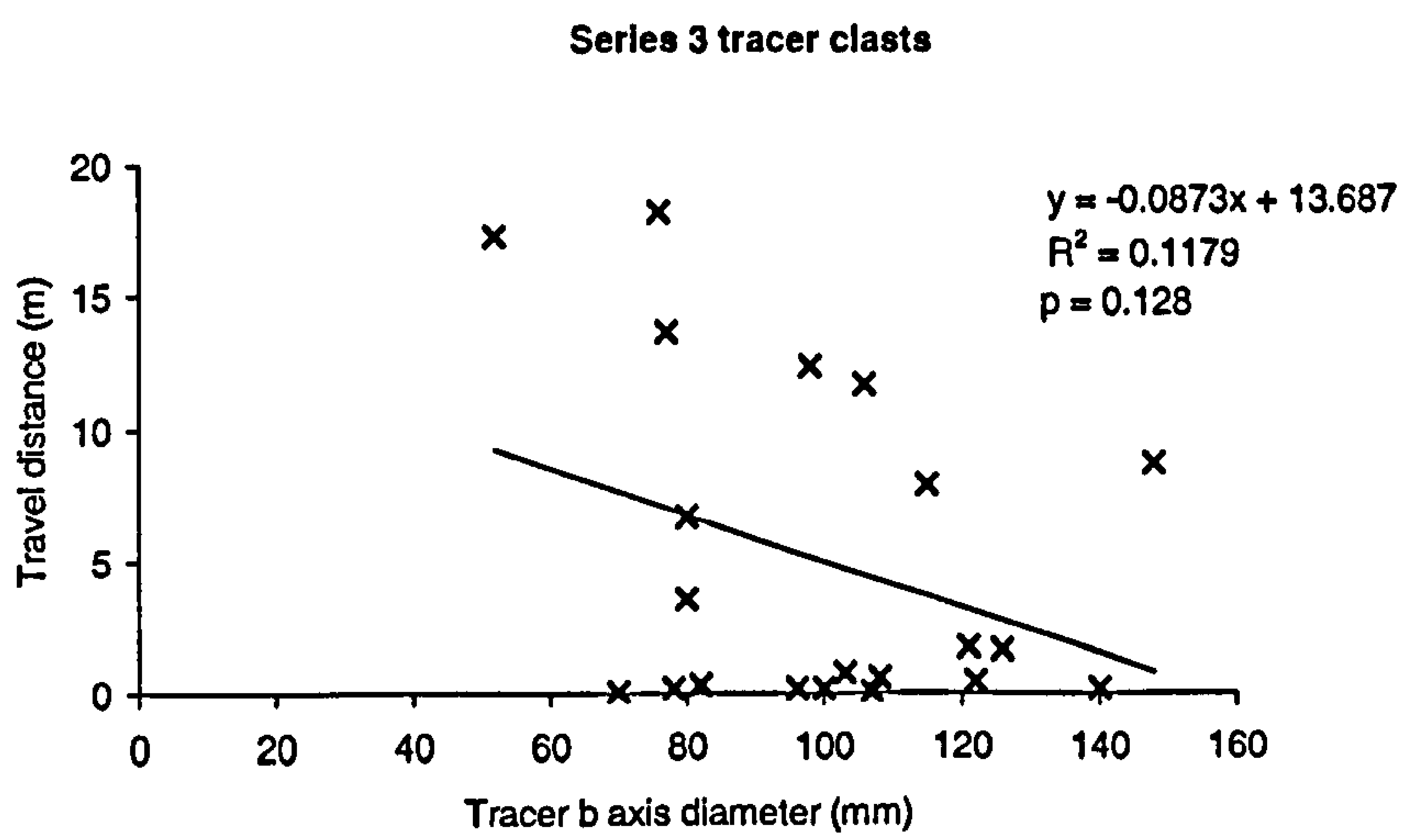


Figure 5.41: Relationship between travel distance and particle size between 13.11.99 and 3.1.00

(A)

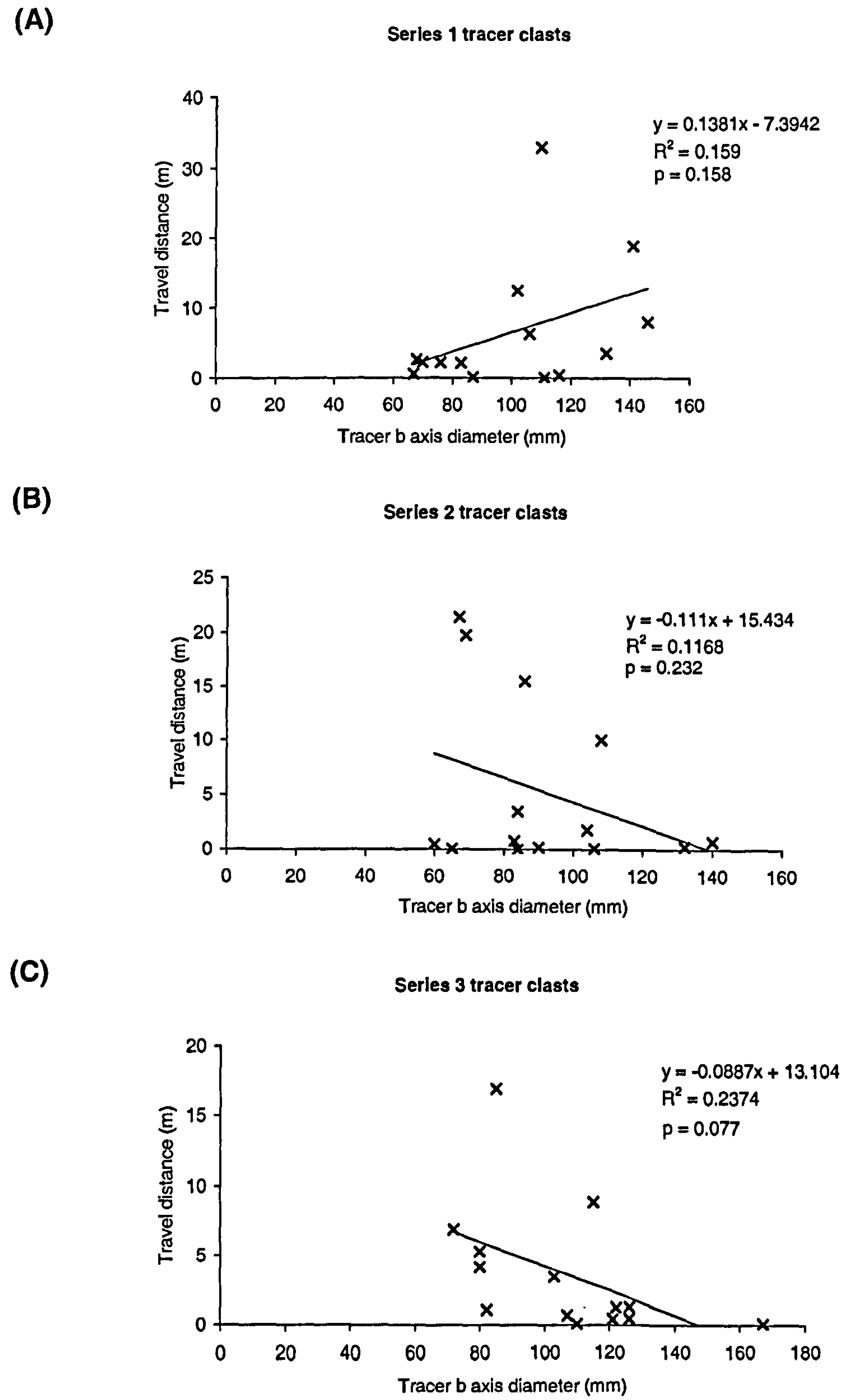
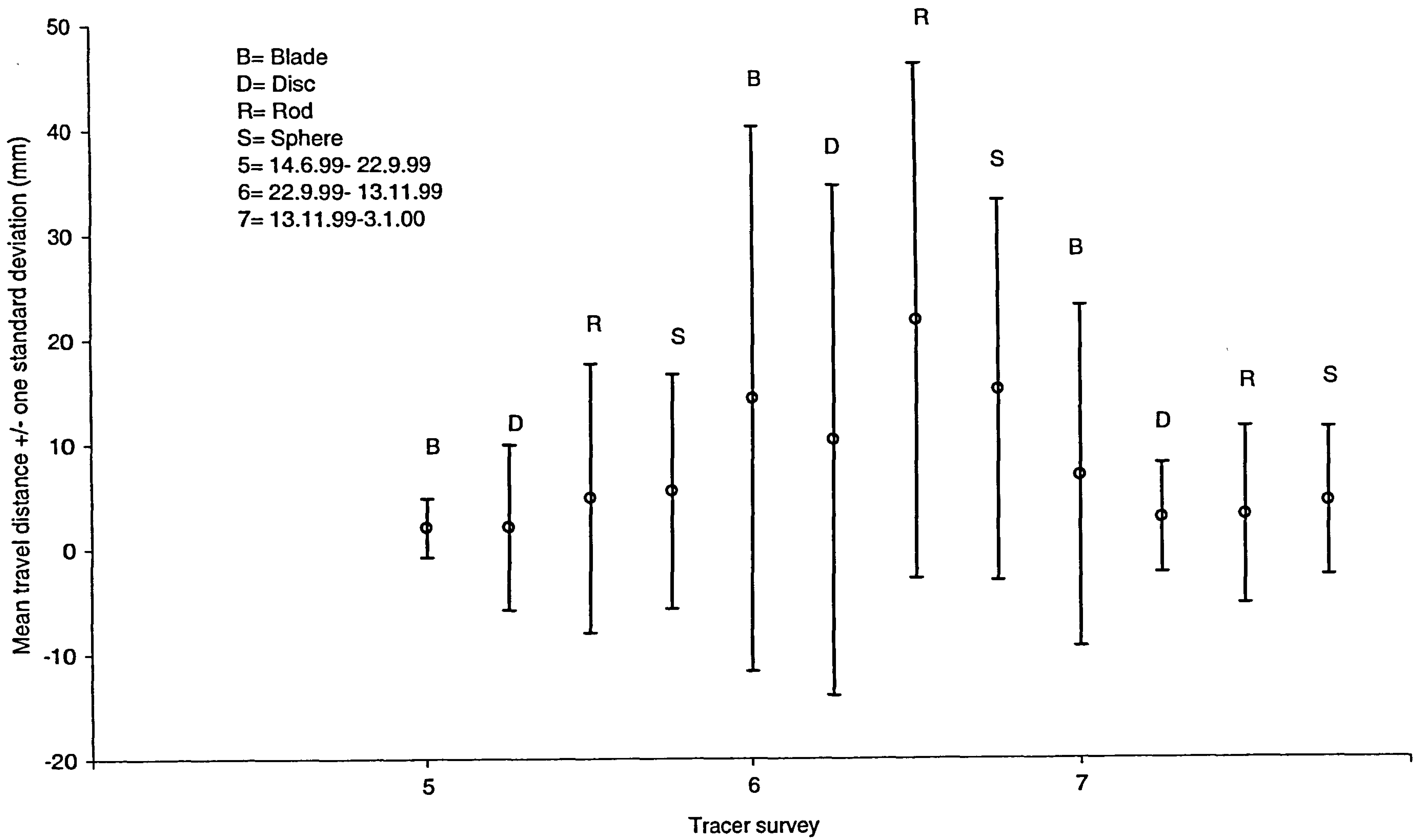


Table 5.21: Travel distances of tracer clasts grouped according to Zingg particle shape classes, between 14.6.99 and 3.1.00

Zingg Shape class	Info	14.6.99-22.9.99	22.9.99-13.11.99	13.11.99-3.1.00
Blade	Number of clasts	11	10	8
	Maximum	8.49	79.67	46.73
	Standard Deviation	2.80	25.96	16.27
	Mean	**2.02**	**14.32**	**6.94**
	Median	0.72	2.40	0.61
Disc	Number of clasts	30	28	26
	Maximum	43.38	112.78	18.96
	Standard Deviation	7.89	24.35	5.24
	Mean	**2.08**	**10.37**	**2.94**
	Median	0.55	1.16	0.37
Rod	Number of clasts	23	21	18
	Maximum	61.65	85.05	32.89
	Standard Deviation	12.80	24.60	8.42
	Mean	**4.85**	**21.76**	**3.19**
	Median	0.94	16.16	0.04
Sphere	Number of clasts	21	21	16
	Maximum	39.63	69.41	21.35
	Standard Deviation	11.16	18.16	7.05
	Mean	**5.49**	**15.14**	**4.46**
	Median	0.61	12.29	1.31

Figure 5.42: Travel distance for tracer segregated according to tracer survey and Zingg particle shape



5.4 Conclusions and recommendations

This chapter adds to a growing understanding of contemporary geomorphological activity in the Caldbeck Fells, having described the different processes contributing to the erosion of the Iron Crag torrent. The annual sediment budget, both in terms of yield and process rates, shows the channel and adjoining banks to be the key components of sediment supply to the fan. The fan, a major storage component, showed strong links to the channel yield dynamics. The erosion of material from hillslopes is considerably less important, even after considering that this study has probably slightly underestimated the slope erosion contribution. Surface wash removal of colluvium and saprolite is more important than the supply of rockfall from crags and cliff faces.

Analyses of the associations of process activity with meteorological conditions reveal that temperature variation influences the rate of rockfall activity, whilst changes in rainfall (runoff) appear to affect channel and bank erosion, and thus by association fan deposition. More significant meteorological events, such as prolonged and heavy rainfall are seen to cause significant geomorphological responses within the system. Differences in sediment-water flow, following meteorological events, alter the magnitude of the morphological response. A channelised debris flow occurring in November 1999 caused large and widespread erosion of the channel bed, whilst during fluvial events the channel erosion is less severe and more localised. The impact of such events will inevitably depend to some extent on sediment availability.

Having constructed the sediment budget a series of recommendations are outlined to help improve the accuracy of future studies. A fundamental necessity in a sediment budget investigation is to have an accurate monitoring design. The design identifies the process activity and interactions, thus influences the sort of monitoring which is conducted. In the case of Iron Crag, despite what was considered a detailed *a priori* knowledge of the system, the delivery of sediment from the primary zone gullies was not fully understood and thus not fully monitored. It is therefore suggested from this experience that preliminary monitoring should form a precursor to a full sediment budget, and where necessary omissions should be rectified by altering the monitoring framework. Preliminary monitoring should also identify important components of the sediment budget, hence the emphasis in the monitoring design can be realigned accordingly. For example, in the case of Iron Crag, the knowledge that the channel and banks are crucial to the system would have lead to a greater number of micro cross sections and bank profiles being used. This would reduce the impact of the spatial extrapolation between cross sections, providing more accurate results, especially as these are non-intrusive measures. Coupled to this would also be a greater number of material property measurements so characteristics such as bulk density can be better quantified.

Erosion pins on both the slopes and banks were not utilised. An investigation of the slope erosion pin results showed them to be inaccurate, primarily as point measurements were being extrapolated to account for changes across a varied and irregular surface. Ideally, far greater densities of erosion pins are required to calculate accurate spatial changes, but this would be impracticable and would probably disturb process activity rather than monitor it. Therefore, it is suggested that a non-intrusive measurement technique is developed to measure topographical changes of hillslopes, such as some form of remote laser measurement, or detailed photogrammetry. Such an approach would also be useful for measuring surface changes of fan deposits.

In addition to problems of design and spatial density of measurement, the issue of the temporal frequency of measurement is very important in sediment budget studies. At Iron Crag a field visit every two to three weeks ensured that the capacity of Gerlach troughs and nets was not exceeded. Nevertheless the hillslope sediment production and other changes in the system were still responses to composite events, i.e. more than one meteorological event, of possibly more than one type. The obvious solution is more frequent observation and measurement, though in the case of Iron Crag this would have meant being there all year, which would not be a realistic option within the financial and logistical constraints within which this study was conducted.

The investigations conducted at Iron Crag were dominated by geomorphological considerations, however the hydrology is important for understanding of the operation of the system. Hence shortly after the completion of the sediment budget monitoring a v-notch weir was built across the channel above the secondary hillslope zone. Continuous measurements of flow stage and suspended sediment load are now recorded by data loggers. Potential applications of these data are: one, establishing the relationship between rainfall (monitored by rain gauge at head of system) and runoff. Two, to investigate the relationship of flow and channel change. Three, measurements of suspended sediment would provide a means to determine the significance of this process in the operation of the system, hence it is of value in assessing the sediment budget. Finally suspended sediment yields would be a valuable addition to the UK database on such process activity.

In more general terms attempts to quantify uncertainty in the sediment budget have shown the need to actively consider the role of error when monitoring process activity. The application and development of remote measurement techniques are recommended as an approach to try and achieve reduction of error in monitoring.

CHAPTER 6: GEOMORPHOLOGICAL HISTORY OF ALLUVIAL PROCESSES AT IRON CRAG

6.0 Scope of chapter

This chapter investigates historical variations in stream channel/ fan processes at Iron Crag over medium (decadal) and long (millennial) time scales, the aims and objectives of which are set out in section 6.1. An analysis of aerial photography in conjunction with contemporary field observation provides a reconstruction of recent process history between 1953 and 2000 (section 6.2). Having established the variety of process activity over the recent past, longer-term changes are considered. Section 6.3 describes the techniques used to categorise process type and assess the age of alluvial sediments. The main body of the investigation is contained in section 6.4; this documents fan stratigraphy (section 6.4.1), provides a temporal framework for the fan sediments, and discusses causes of aggradation (section 6.4.2), and finally the Iron Crag fan chronology is compared to other British alluvial fan and debris cone chronologies (section 6.4.3). Section 6.5 concludes the chapter and links contemporary rates of fan deposition to historical process rates.

6.1 Aims and objectives

The overall aim of this chapter is to determine the long-term activity at the Iron Crag alluvial fan. Field observations, medium-term aerial photograph archives combined with analysis of palaeo-fan deposits, evident downslope of the mine level in the area reactivated during the pre-1970 event, provide the basis of this assessment. The objectives of this reconstruction are threefold:

1) To establish the type and frequency of process activity operating across the fan.

2) To calculate rates of accretion through time on the fan surface.

3) To compare the Iron Crag fan chronology to other British alluvial fan/ debris cone complexes.

6.2 Aerial photograph analysis

A series of vertical aerial photographs taken between 1953 and 1995 provide an opportunity to reconstruct the process activity in the lower reaches of the Iron Crag sediment system (downstream of secondary source) over a medium-term time scale. Table 6.1 outlines details of the available aerial photography for Iron Crag over a 42 year period. In all six aerial photographs are available: 1953, 1970, 1983, 1984, 1988, 1995. Subsequent to 1995 field observations between October 1997 and October 2000 provide further details on the most recent fan activity and associated form changes.

Table 6.1: Details of vertical aerial photographs showing the Iron Crag alluvial fan complex between 1953 and 1995.

Aerial photograph	Date	Scale	Source
1953	21.04.53	1: 10,000	RAF
1970	14.06.70	1: 7,500	Ordnance Survey
1983	10.08.83	1: 10,000	ADAS/ MAFF
1984	5.07.84	c. 1: 12, 500	Cambridge Uni.
1988	11.05.83	1:18,000	ADAS
1995	6.05.95	1: 8,000	Ordnance Survey

In 1953 fan activity was limited. No channel is visible beyond Lainton's Engine shaft (mine level), and overbank deposits are largely confined to above the mine level (Figure 6.1 A). Deposits on the right bank of the channel begin just after the end of the secondary hillslope zone and spill on to the upper part of the mine level. On the left bank a small linear sediment lobe also extends from just after the end of the secondary hillslope zone to just downslope of the mine level track. (Figure 6.1 A).

Between 1953 and 1970 a major change occurred in the system. Figure 6.1 B shows fan deposits once more starting from just below the secondary zone, but extending well beyond the mine level. These changes are reflected in the increase in the estimated areas of deposition; increasing from 840 m^2 in 1953 to 2445 m^2 in 1970, a threefold increase. This increase in deposit area can be attributed to fresh deposition, even above the mine level, as the 1953 deposits are largely revegetated. Below the mine level two new lobes of sediment are deposited.

By 1983 deposition of sediment largely occurred below the mine level. There is a slight increase in deposit area between 1970 and 1983. The right bank deposit develops a new lobe of sediment, running between right and left lobes deposited in 1970. The left bank deposit shows signs of re-vegetation in the lower toe areas.

The 1984 aerial photograph shows a pattern of deposition very similar to that which existed in 1983. A small amount of re-vegetation has occurred, which accounts for some of the deposit area reduction, although some of the difference may also relate to the poorer quality of the 1984 photograph.

In 1988 re-vegetation of the 1970 left bank deposit and the original right bank lobe appears well developed. Closer examination reveals fresh deposit further down slope than those which existed in 1984 (Figure 6.1 D, F: label 1) (also see Figure 36, Cooper and Stanely, 1990). This implies more transport and deposition of material in this part of the fan. The existence of debris flow levee deposits identified on the fan (Figure 6.1 F: labels 2 and 3, Figure 6.2) in March 1998 probably relate to event(s) between 1984 and 1988. The levees located by label 2 form a rectangular shape that is evident on the 1988 and 1995 photos but not before this period.

By 1995 the incised fan head feeder channel running beneath the mine level is very evident (Figure 6.1 F: label 4), and shows more development than previously. This contributes sediment to an enlarged right-side debris cone, though below this point the area of visible 'fresh' deposit is less. By 1995 virtually none of the 1970 left-bank lobe is visible and the right-bank deposits after the cone are dominated by the 1988 deposits. Therefore the area of deposit is reduced by 754 m^2 between 1988 and 1995.

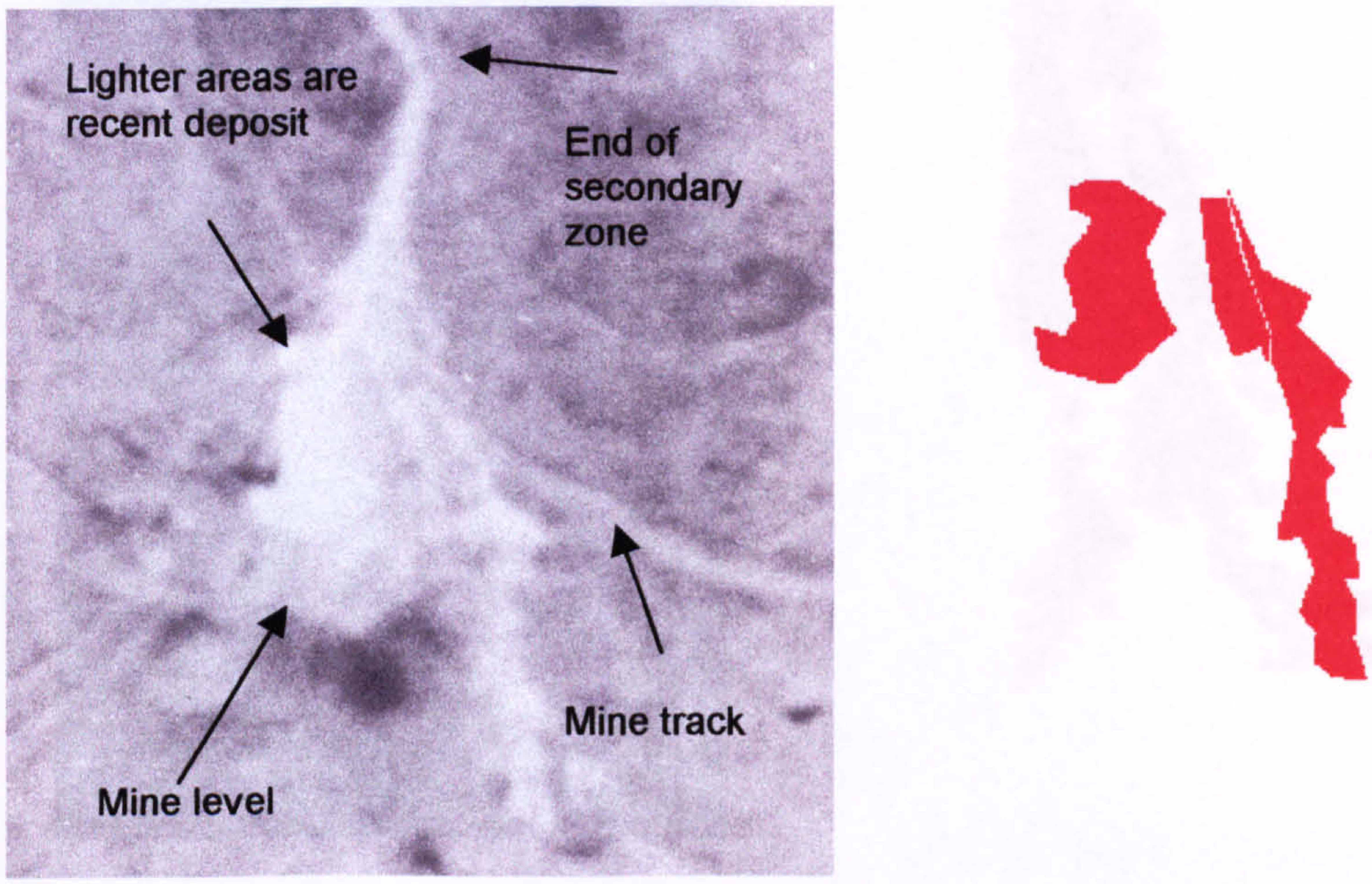
After 1995 incision of the upper fan surface beneath the mine level continued, producing a narrow sinuous channel in the right bank cone (Figure 6.1 F: label 5). This feature existed in October 1997 but is not evident on the good quality 1995 photograph. Between October 1997 and October 2000 the channel increased in both capacity and width due to bank failures, channel incision and erosion by sheep. Incision has isolated the 1995 sediment cone allowing this to start to revegetate, and has formed a new cone immediately below the distal end of the incision. Figure 6.3 illustrates the development of incision between January 1998 and January 2000. This extended channel provides a conduit for the delivery of sediment to the lower part of the fan by fluvial processes. This was observed in Autumn 1999 when several events deposited large quantities of sediment on the fan leading to an expansion of the active fan area (see Chapter 5).

Figure 6.4 shows the changing location of the fan apex during the 1953-1998 period. As described previously the fan migrates downslope, most especially between 1984-1988, and 1995-1998. The most recent downslope advance is due to the channel incision and the formation of a new 'active depositional lobe' in the terminology of Blair and McPherson (1994). Overall during the 47-year period of photography and observation the fan and associated channel system has been very active; with the fresh alluvial deposition after 1970, debris flow activity in the mid 1980s, and frequent fluvial activity (most evident during fan apex incision in the late 1990s). Such varied activity in the medium-term suggests that an investigation of the process activity over longer timescales would be beneficial in understanding of the operation of the Iron Crag system. Further, this would enable the detailed contemporary study of Iron Crag (Chapter 5) to placed in a wider temporal framework, since linking the contemporary and historical timescales is a key step in evaluating the significance of the contemporary sediment budget.

Figure 6.1: Aerial photographs showing the lower part of the Iron Crag system, and corresponding area measurement images showing the extent of deposition (Scales variable).

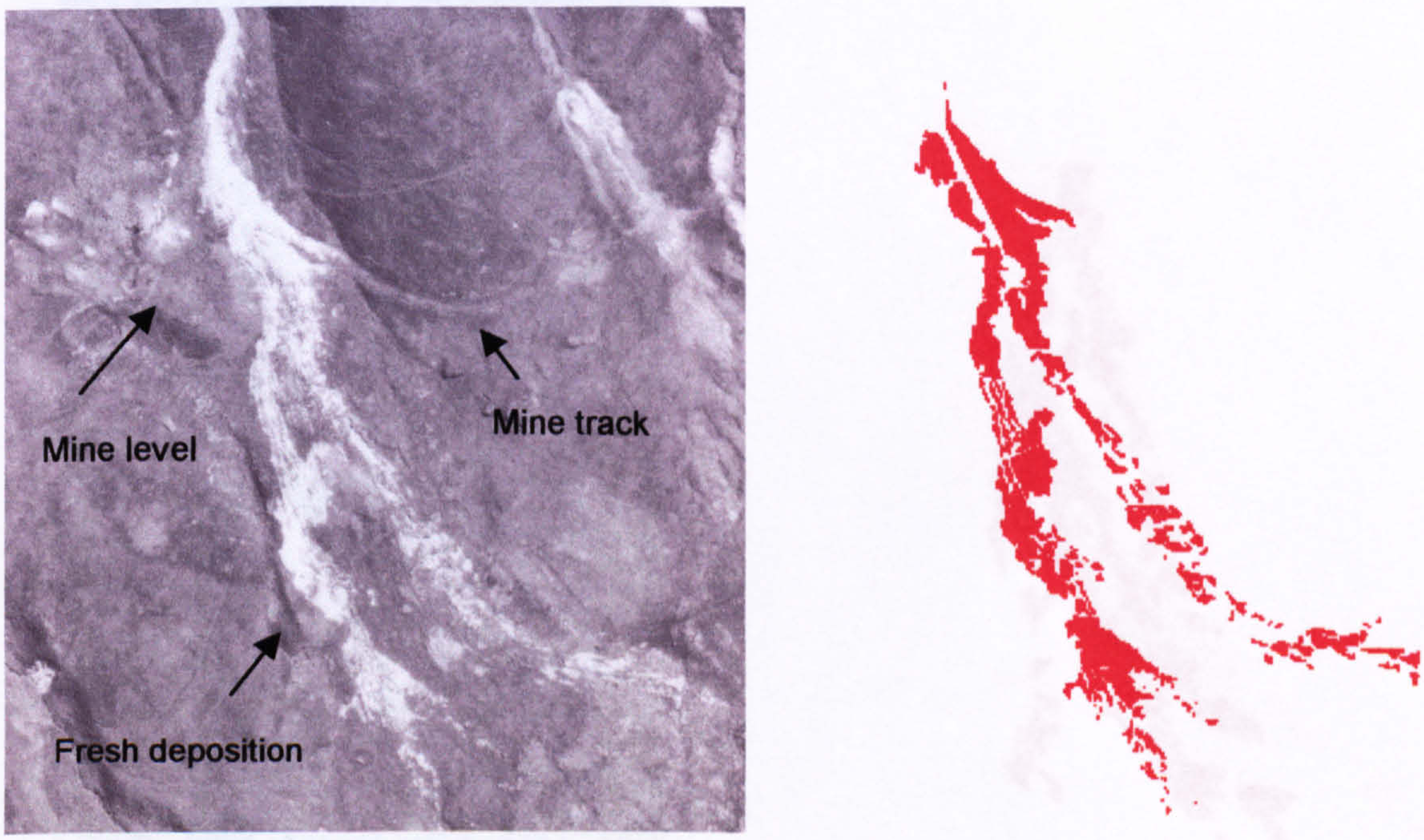
A (1953)

Deposit area = 840 m^2



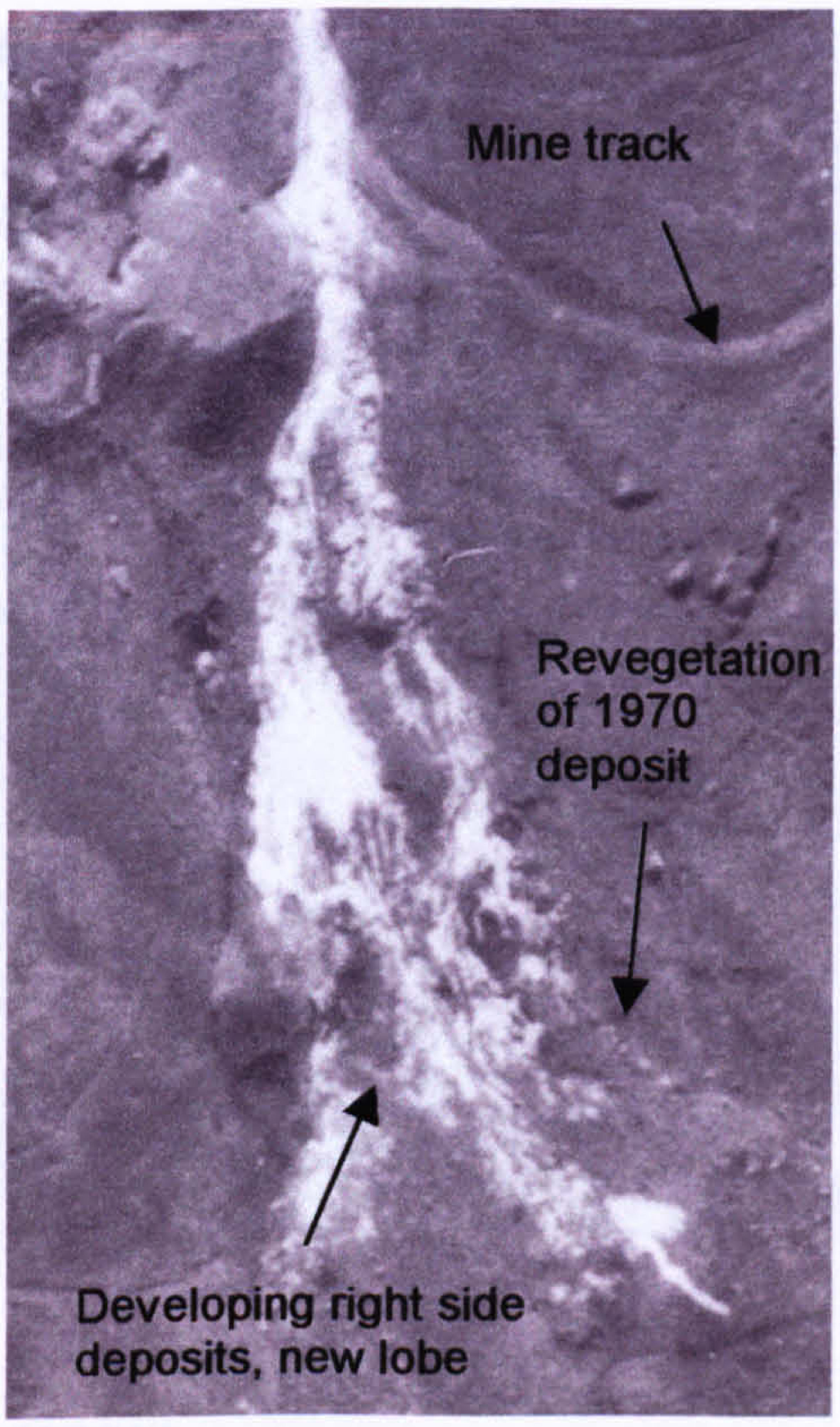
B (1970)

Deposit area = 2445 m^2



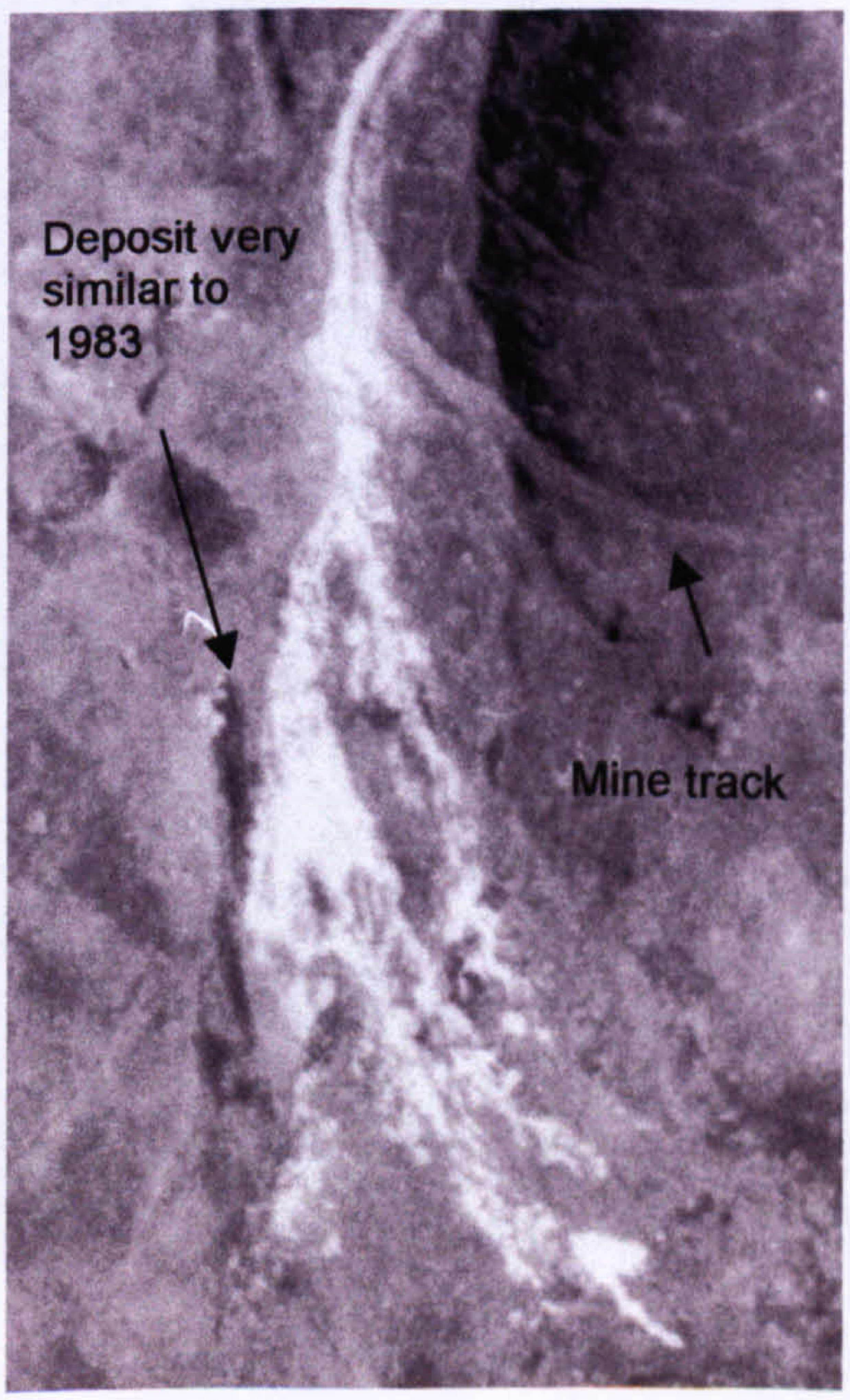
C (1983)

Deposit area = 2552 m^2

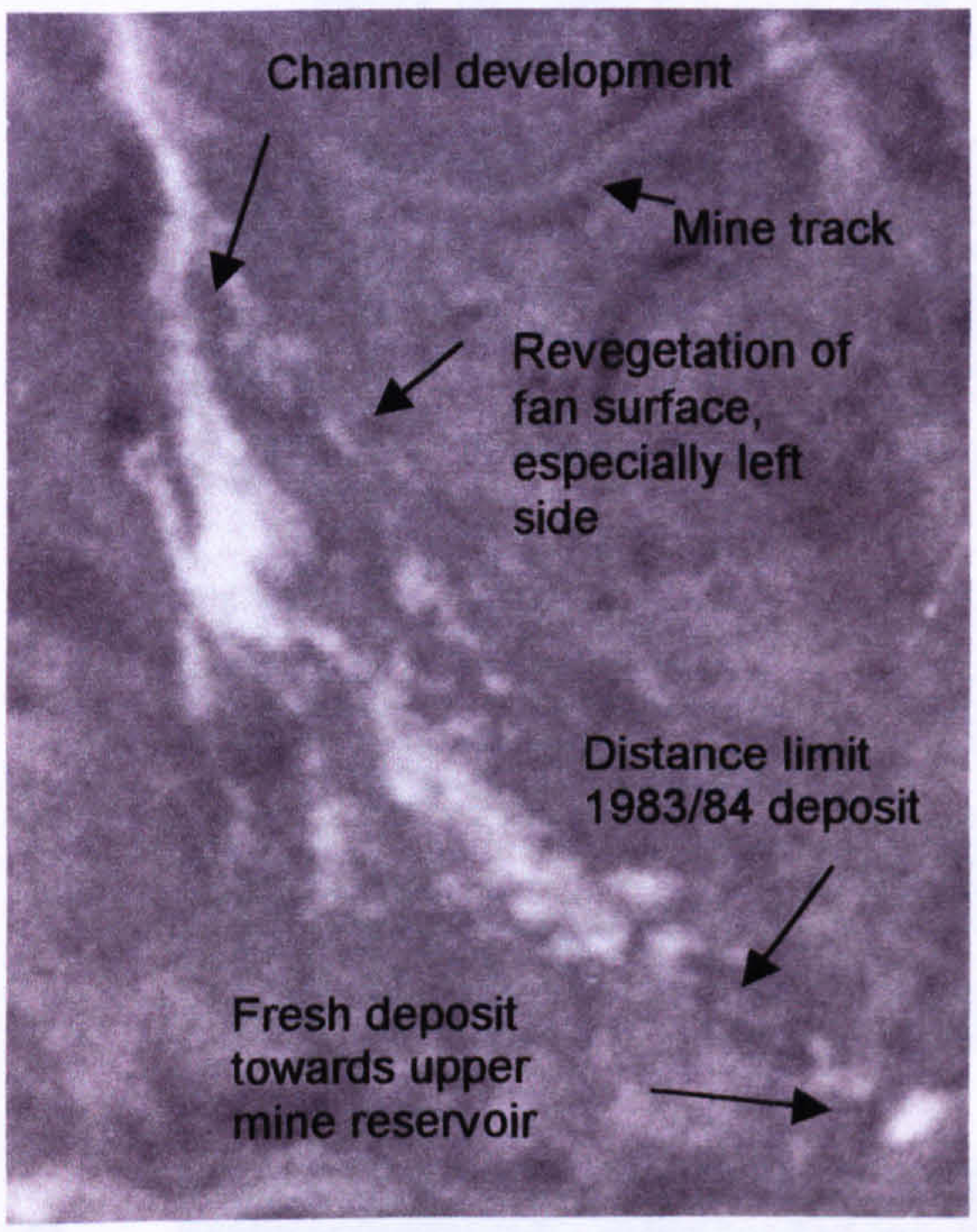


D (1984)

Deposit area = 2140 m^2

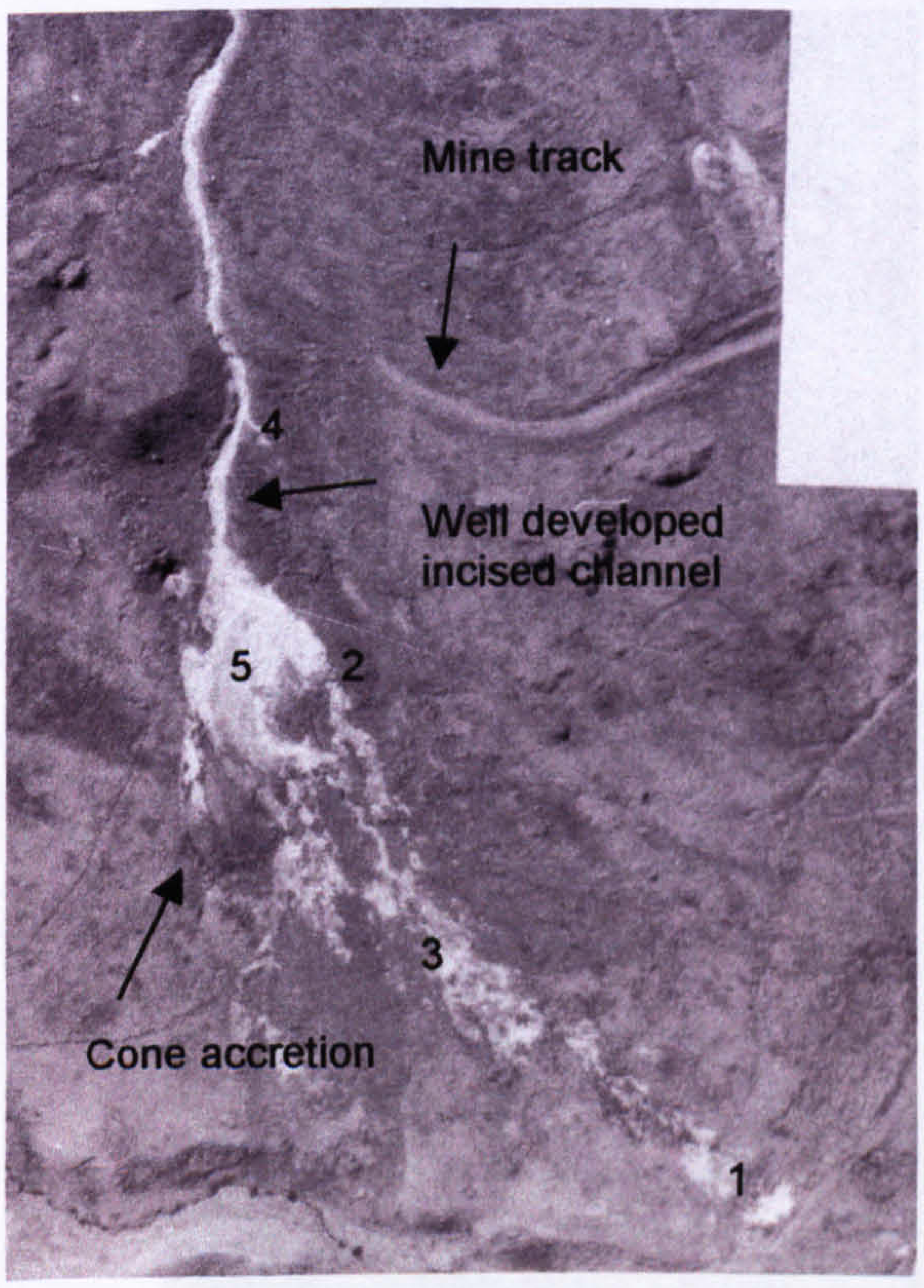


E (1988)



Deposit area = 2307 m^2

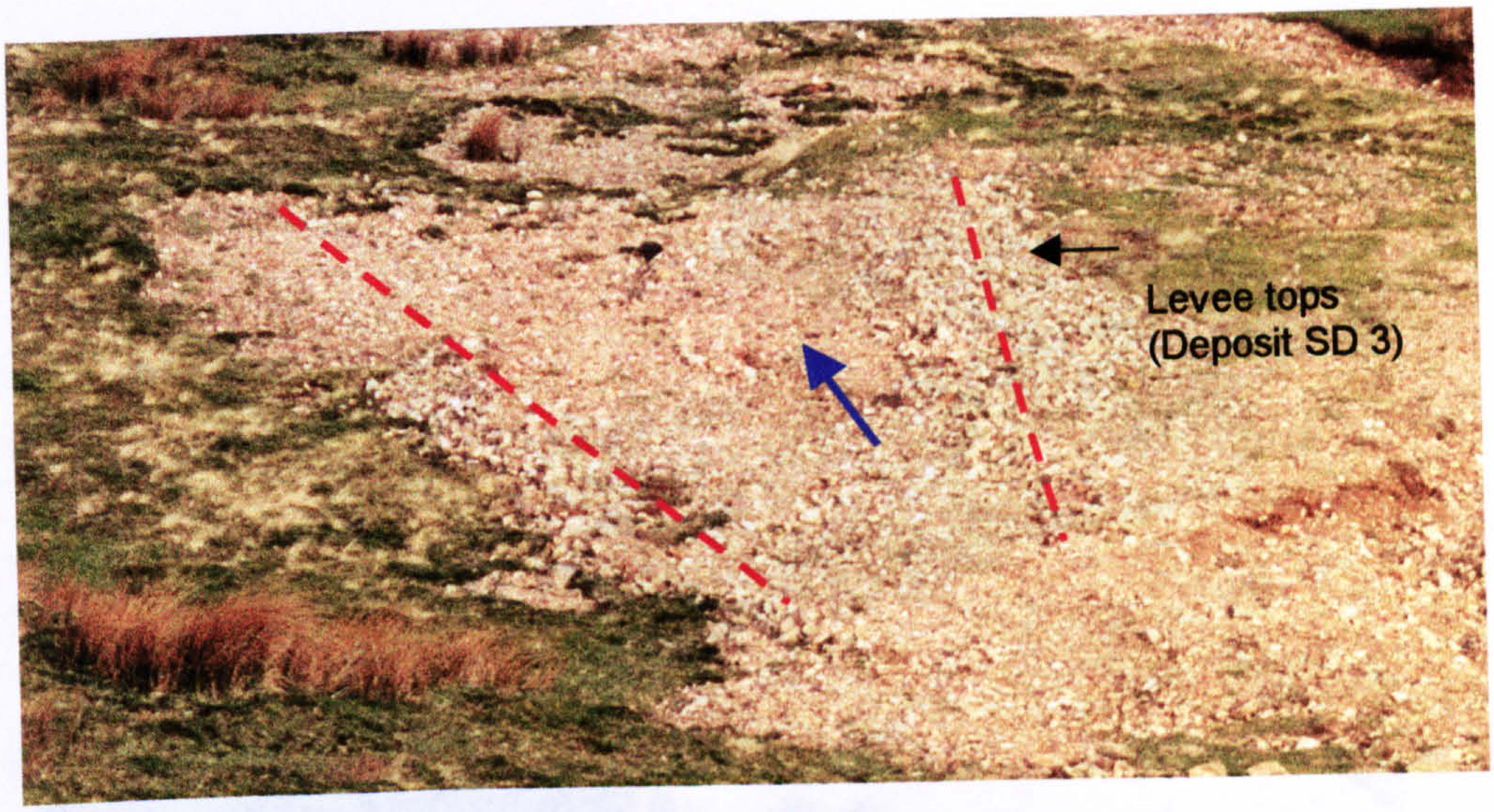
F (1995)



Deposit area = 1553 m^2

Figure 6.2: Paired debris flow levee deposits, of probable 1984-1988 age. [A- higher levee-label 2 on Figure 6.1, F; B- lower levees-label 3 on Figure 6.1, F.] Red dashed lines show the axes of the levees, and blue arrows the flow direction.

A



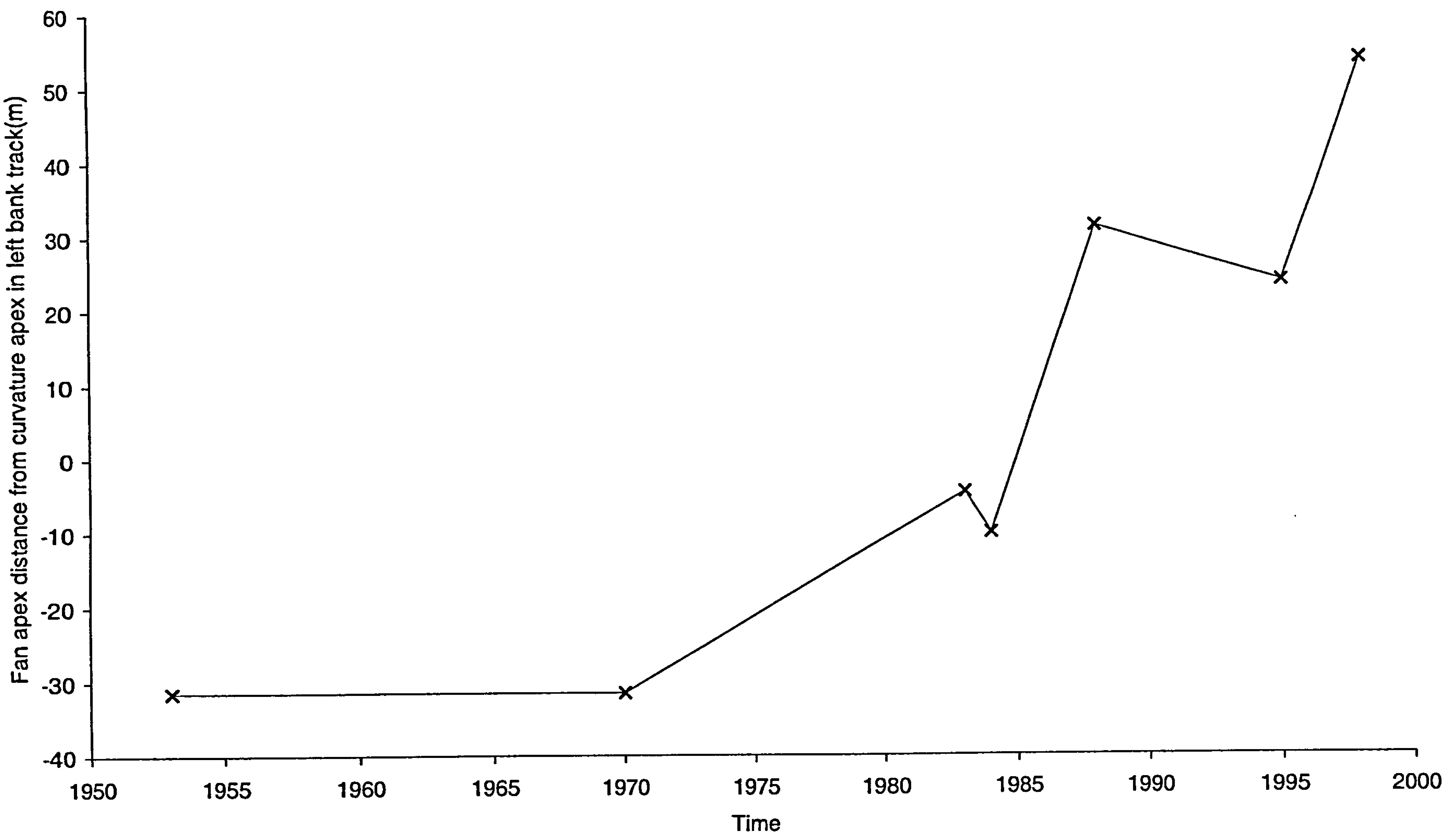
B

Figure 6.3: Development of fan apex incision, showing noticeable increases in width and depth (A- 1.1.98; B- 6.1.00). Both views looking downstream, as indicated by blue flow direction arrows.

A

B

Figure 6.4: Migration of fan apex deposit



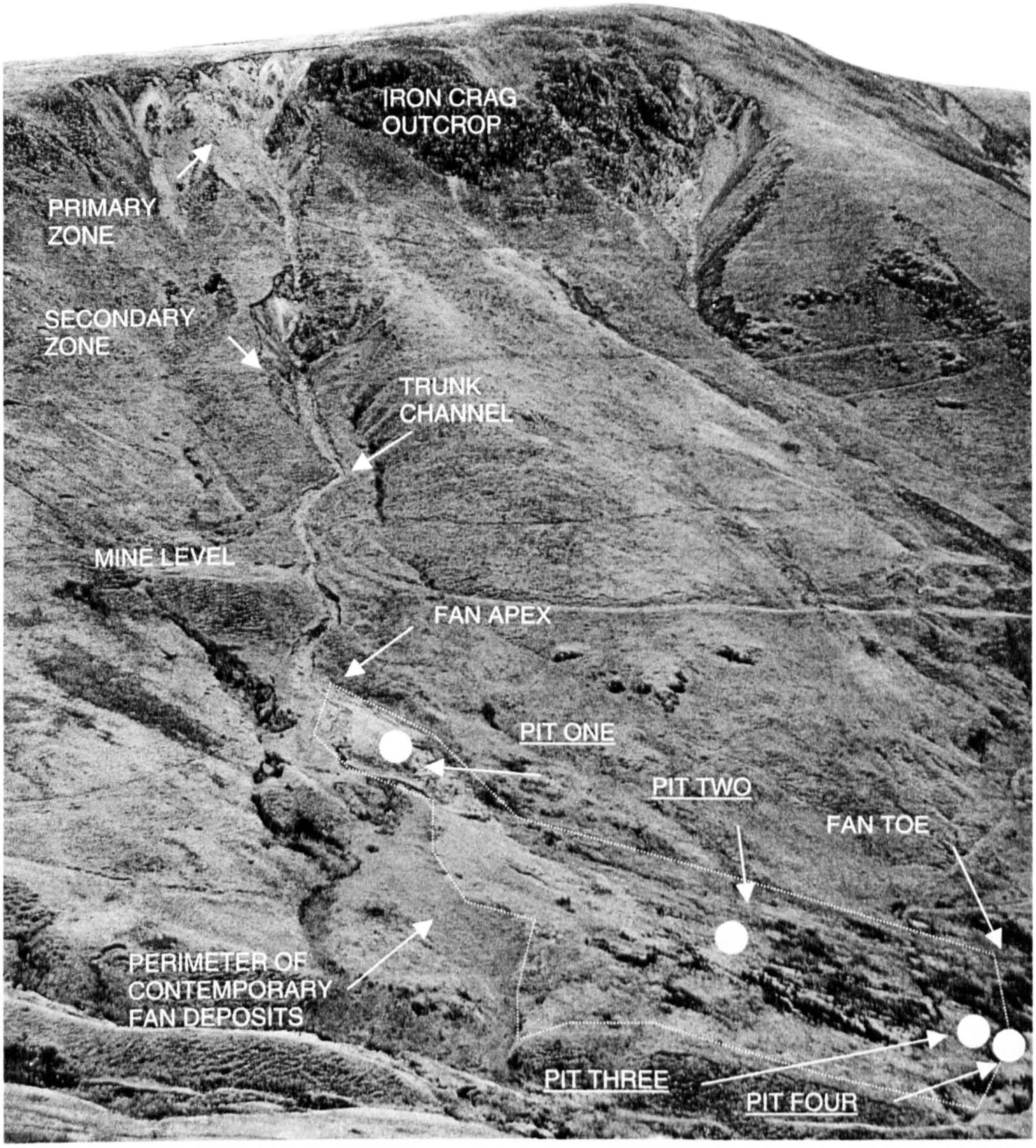
6.3 Methods used to reconstruct the fan history

A variety of techniques have been used to reconstruct process histories at geomorphological sites. These have generally used a combination of sediment characteristics, such as particle size, stratigraphic description (e.g. Wells and Harvey, 1987; Costa, 1988; Davis, 1992; Scott *et al.*, 1995; Hinchcliffe *et al.*, 1998), and other properties (e.g. loss on ignition, pollen analysis, magnetic susceptibility, radiocarbon dating) to show variations over time (e.g. Harvey *et al.*, 1981; Brazier *et al.*, 1988; Tipping, 1994; Tipping and Halliday, 1994; Ballantyne and Whittington, 1999). Such an approach is used at Iron Crag for analysing the fan sediments exposed in four pits spaced along the fan axis from the fan apex (beneath the mine level) to the fan toe (just above the upper mine reservoir) (see Figure 6.5 for pit locations). The following sections briefly outline the techniques as applied at Iron Crag.

6.3.1 Particle size analysis

The analysis of particle size is discussed fully in Chapter 4, in terms of its value for process determination. One critical difference here is that in addition to the sieve and calibre plates a Coulter granulometer was used to measure particle size to the silt clay boundary (+ 9 ϕ). Also, Chapter 4 distinguishes the particle size characteristics of sediments associated with different dominant process types determined from meteorological data and field observations. Here, particle size characteristics of contemporary process deposits are compared to the particle size characteristics of fan sediments. The contemporary process deposits (type sediments) were identified; described and sampled for particle size analysis in March 1998 and November 1999. Samples included: debris flow levees (channel side and on fan surface); debris flow lobes; and fluvial sediments from both in channel and sheet deposits on the fan surface. Assuming the source of the sediments for accumulation on the fan has remained relatively constant throughout its history, it is reasonable to expect that the particle size signatures of fan deposits would be similar to the characteristics of the type sediments. As in Chapter 4 three diagnostic parameters are used to specify the characteristics of sediments from particle size curves, namely: graphic mean

Figure 6.5: A view of the Iron Crag torrent system taken from Peteraw (NY 303 348, 500 m O.D.), illustrating the location of the fan Pits in relation to the sediment supply system.



diameter; inclusive graphic standard deviation (sorting); and skewness. Following the convention established by Folk (1968) these graphic statistics are reported in phi units.

6.3.2 Stratigraphic description

In addition to the quantitative characterisation of sediments, field interpretations and stratigraphic logs provide valuable information for the assessment of process activity. Field observations identify features in each stratigraphic layer, which include: the mechanism of particle support, grading direction, sorting, evidence of imbrication, and the existence of megaclasts. These criteria help establish whether the deposit is of debris flow or fluvial origin, or an alternative such as a fine-grained alluvium or soil horizon. The sedimentological criteria that differentiate water floods from debris flows is summarised in Table 6.2. In general terms fluvial deposits tend to be imbricated, clast-supported, well sorted and fine upwards. Conversely debris flows are matrix-supported, occasionally show inverse grading (fining downwards), are poorly sorted, and lack imbrication.

6.3.3 Loss on ignition (LOI)

The organic carbon content of a sample helps determine the amount of plant organic material (Gale and Hoare, 1991) and aids in the identification of palaeosols. Lowe and Walker (1997) state that organic content is also useful for establishing the amount of organic material required for radiocarbon dating. Gale and Hoare (1991) advocate the use of 'loss-in-mass' procedures for determining the organic content. A modified version of their procedure is adopted here, where a crucible and sample of known mass are air dried at 105 °C for 24 hours in an oven. The sample is cooled, re-weighed, and placed in a pre-heated furnace at 550 °C for 4 hours, followed by a final cooling and re-weighing. The loss on ignition percentage is as follows (McRae, 1988):

Table 6.2: Compilation of sedimentological criteria for differentiating water floods and debris flows.

Author(s)	Water floods	Debris flows
Johnson & Rodine (1984)		-deposit margin composed of coarse clasts -successive layers from one event get finer -fine upward grading -platy clast orientated so that long and intermediate axes are parallel to the outer edges of the flow
Wells and Harvey (1987)	-weak to strong imbrication -clast supported -weak to well sorted -graded sheet deposits	-matrix rich -matrix supported -poorly sorted -stratification absent -possibly clast orientation forming a push fabric -levees- internal sorting
Costa (1988)	-horizontal or inclined stratification to massive -weak to strong imbrication -cut & fill structures -ungraded to graded -Trask sorting coefficient: 1.8 -2.7 -clast supported -normally distributed -rounded clasts -wide range of particle sizes	-no stratification -no to weak imbrication -inverse grading at base, normal grading near top -Trask sorting coefficient: 3.6-12.3 -graphic sorting coefficient: 3.0-5.0 -matrix supported, but clast supported if matrix drains away -skewed particle size distribution -extreme range of particle sizes -possible megaclasts
Davis (1992)	-stratification & imbrication -cut & fill -dominated by gravel & sand -gravel concentrated at base	-poorly sorted -no preferential removal of certain size clasts -only stratification if succession of flows
Scott *et al.* (1995)		-matrix of sand, clay, silt. Clay up to 5% in cohesive debris flow -Non-cohesive debris flows (1% clay) distinctive sole layer, inverse graded bedding, truncated size distributions.
Coussot & Meunier (1996)		-negligible grading and internal structure
Keaton & Mathewson (1998)	-eroded basal contact -fining upward graded bedding	-uneroded basal contacts -fully matrix supported -unsorted -unstratified -isolated megaclasts -psuedolamination in basal shear zone

$$LOI (\%) = (M_d - M_c / M_c - M_a) \times 100$$

where- M_d = cooled post furnace mass of crucible and sample (g to 10^{-3})
M_c = cooled post oven mass of crucible and sample (g to 10^{-3})
M_a = mass of crucible (g to 10^{-3})

6.3.4 Pollen analysis

Lowe and Walker (1997) consider pollen analysis to be one of the most widely used and versatile techniques for reconstruction of Quaternary environments. Furthermore, the technique allows the reconstruction of vegetation history, an assessment of human activity on the landscape, and the correlation of stratigraphic units. It also enables approximate ages to be estimated. Local indicator species and assemblages from a total pollen count can be cross referenced to local, regional and national pollen diagrams which have radiocarbon dated horizons. Simmons and Tooley (1981), Berglund (1986), Faegri and Iversen (1989), and Moore *et al.* (1991) all give further details concerning the application of this technique. At Iron Crag palynology provides an indirect means of dating fan sediments and provides evidence of the impact of human activity on the local/ regional vegetation composition.

6.3.5 Magnetic susceptibility

Dearing (1994) states that, at the simplest level, magnetic susceptibility is a measure of how magnetizable a material is, which in rocks is a function of their mineralogical composition. The magnetic susceptibility of any sample is the sum of the constituent magnetic behaviour. This is measured by the ratio of an imposed magnetic field to the amount of magnetization created in a sample under the influence of the magnetic field (Dearing, 1994). A Bartington MS2B sensor was used to measure the magnetic susceptibility of Iron Crag pit sediments. This is performed using fixed volume (10 cm^3) magnetically inert plastic pots. Dry, less than 2 mm grade sediment, is packed in to the pots to minimise void spaces, and given the assumption that packing densities are similar, volume susceptibilities are obtained. Varying densities of the materials result in different sample masses. To take this factor into account mass specific susceptibility (χ lf) is calculated, and expressed in units of μ m^3 kg^{-1}. This very brief review of the magnetic susceptibility provides no discussion of the assumptions and limitations of the technique, the treatment of samples to minimise contamination, or the measurement of volume susceptibility values using the MS2 B. All are considered in more detail in Dearing (1994) and Bartington (1997).

It is hypothesised that mining activity at the site may have produced a magnetic susceptibility peak within the fan sediments, thus providing a temporal control and a further indicator of human influence on the development of the Iron Crag fan. Such increases in bulk susceptibility/ metal content are commonly found in horizons dominated by mining sediments (e.g. Macklin *et al.*, 1992).

6.3.6 Radiometric dating

Lowe and Walker (1997, p238) outline the basis of radiometric dating:

"Radiometric dating methods are based on the radioactive properties of certain unstable isotopes which undergo spontaneous changes in atomic organisation in order to achieve a more stable atomic form...Radioactive decay (atomic transformation) is time dependent, and if the rate of decay is known, the age of the host rocks or fossils can be established."

Radiometric dating is a common technique used to establish the age of alluvial sequences. However there have been relatively few dates on upland alluvial fan sediments (Harvey *et al.*, 1981; Harvey and Renwick, 1987; Brazier *et al*, 1988; Brazier and Ballantyne, 1989; Tipping and Halliday, 1994; Dunsford, 1998; Ballantyne and Whittington, 1999). More detail outlining the use of radiometric dating, specifically Carbon 14 (^{14}C) activity, is provided by Worsley (1990); and Lowe and Walker (1997). At Iron Crag palaeosols and wood fragments were dated by the NERC Radiocarbon Laboratory at East Kilbride. The resulting four radiometric dates (SRR-6599; SRR-6600; SRR-6601; and SRR-6602) and one AMS date (AA-39694) are discussed in later sections.

6.4 Historical fan activity

This section attempts to identify process variations from fan sedimentology (6.4.1), provides a temporal framework for the process variability (6.4.2), and compares the Iron Crag fan chronology to other UK fan histories (6.4.3).

6.4.1 Process identification using pit stratigraphy and sedimentology

6.4.1.1 Type sediments

The type sediments were mostly sampled in March 1998; however, with the occurrence of a fresh channelised debris flow in November 1999 the opportunity to collect further particle size data was taken. Table 6.3 summarises the main statistical attributes of the particle size analysis of these type sediments. The samples taken in March 1998 cover the entire size range of the deposits. The November 1999 deposits are largely restricted to the matrix sediment and exclude some of the coarsest clasts at the top of the levees. This sampling difference is reflected in the statistics, as levees from November 1999 show a smaller proportion of gravel (79.50 %) compared to the March 1998 deposits (88.75 %). The lower amount of gravel is offset by an increase in sand, silt and clay-sized particles. This fining is reflected in smaller values of both mean and median particle size in the November 1999 sediments -3.32 ϕ (9.99 mm), -4.42 ϕ (21.41 mm), respectively. Given the shortcomings of the November 1999 sampling, only the sediments collected in March 1998 can truly be used as 'type' sediments for the identification of process type in the pit sediments.

Considering the debris flow and fluvial sediments of March 1998, a clear separation of the deposits is apparent from the statistics. Debris flows are coarser (mean -4.30 ϕ [19.7 mm]; D_{50} -5.08 ϕ [33.82 mm]) than fluvial deposits (mean –0.95 ϕ [1.93 mm], D_{50} –0.96 ϕ [1.95 mm]). Similarly debris flows show greater positive skewness (0.64 ϕ) than fluvial deposits (0.19 ϕ) (i.e. negative statistical skew). These skewness values indicate that both deposit types have a dominance of coarse particles with a fine tail, but this asymmetry to greater size particles is more developed for debris

Table 6.3: Summary particle size statistics of type sediments, computed using SIZEDATA and SEDSIZE (Stevens and Hubbell, 1986) (March 1998 deposits = date of sample collection; November 1999= date of formation and sample collection) (SD= field labeling scheme meaning sediment deposit) (*1= No program output because of operating rules)

Process Type	Label and description	Mean (Phi units)	Sorting (Phi units)	Skewness (Phi units)	Median (D_{50}) (Phi units)	% Gravel	% Sand	% silt and clay
Debris Flow (March 1998)	SD 6 (Lobe front)	-4.329	2.027	0.649	-5.212	87	11	2
	SD 3 (Levee channel)	-3.175	2.38	0.108	-3.289	73	25	2
	SD 7 (Levee)	-4.053	2.879	0.799	-5.441	82	13	5
	SD 1 (Levee)	-5.361	1.523	0.886	-6.003	92	7	1
	SD 3 (Levee)	-4.581	2.779	0.756	-5.445	89	2	9
	Average	**-4.30**	**2.32**	**0.64**	**-5.08**	**84.60**	**11.60**	**3.80**
Debris Flow (Nov. 1999)	B (Lobe)	-5.06	0.592	0.4	-5.198	-*1	-*1	-*1
	C (Lobe)	-2.769	2.271	0.409	-3.264	77	21	2
	E (Lobe)	-4.78	1.289	0.68	-5.115	93	6	1
	F (Lobe)	-5.222	1.094	0.821	-5.52	94	6	0
	G (Lobe)	-4.612	1.905	0.759	-5.505	91	8	1
	Average	**-4.49**	**1.43**	**0.61**	**-4.92**	**88.75**	**10.25**	**1.00**
	A (Levee)	-3.721	2.603	0.866	-5.241	80	18	2
	D (Levee)	-2.91	2.262	0.515	-3.591	79	19	2
	Average	**-3.32**	**2.43**	**0.69**	**-4.42**	**79.50**	**18.50**	**2.00**
Fluvial (March 1998)	Wash deposit over snow	0.283	1.807	0.401	0.055	15	77	8
	SD 4 (Wash on fan)	-1.046	2.165	0.102	-0.939	48	46	6
	SD 5 (Fan cone)	-2.091	2.341	0.059	-1.994	67	30	3
	Average	**-0.95**	**2.10**	**0.19**	**-0.96**	**43.33**	**51.00**	**5.67**

flows than fluvial flows reflecting their poor sorting. This finding, that positive skewness is a characteristic of debris flow deposits, concurs with the work of Sharp and Nobles (1953) and Scott (1971) who found skewness a good textural indicator of debris flow sediments.

The sorting value (inclusive graphic standard deviation) shows most debris flow deposits to be very poorly sorted (category range 2-3.99 ϕ), but counter to expectation so are the fluvial deposits. In both cases the average sorting values are too close to be used as a means of process division (2.32 ϕ debris flow; 2.10 ϕ fluvial). Hence the best combination of graphic statistics for the identification of process type at Iron Crag are the mean size and the skewness, as these show the greatest separation in the type sediments.

Figure 6.6 shows the differences between debris flow and fluvial deposits plotted in a bivariate relationship between mean size and skewness; clear process clustering is apparent, as are subtle differences. Deposit SD 3 is sediment taken from in between two paired levees and plots away from the debris flow grouping and nearer to the fluvial deposits. SD 3 is probably different due to subsequent fluvial modification of this channel basal deposit, and therefore should not be considered as a true indicator of debris flow sedimentology. The small number of fluvial-type sediments also show some variability, with the fan deposits being coarser and less asymmetric than the snowmelt fines found higher up in the channel. Despite the small number of samples, clear division between fluvial and debris flow activity is identified. This is further supported by Figure 6.7 that shows field examples of the March 1998 type sediments. Hubert and Filipov (1989) also used a bivariate relationship between mean size and skewness of the entire particle size distribution to identify five depositional facies, and like Figure 6.6 their results showed a separation of fan alluvium (defined as fine fluvial deposit) and debris flow deposits. In contrast to the trends found at Iron Crag, Hubert and Filipov (1989) show fluvial deposits to be coarser and have greater positive skew than debris flows. This difference probably reflects local variabilities such as material type and process scale. This emphasises the need for 'local' sediments in identifying process types.

Figure 6.6: Relationship between mean particle size and sorting for March 1998 type sediments

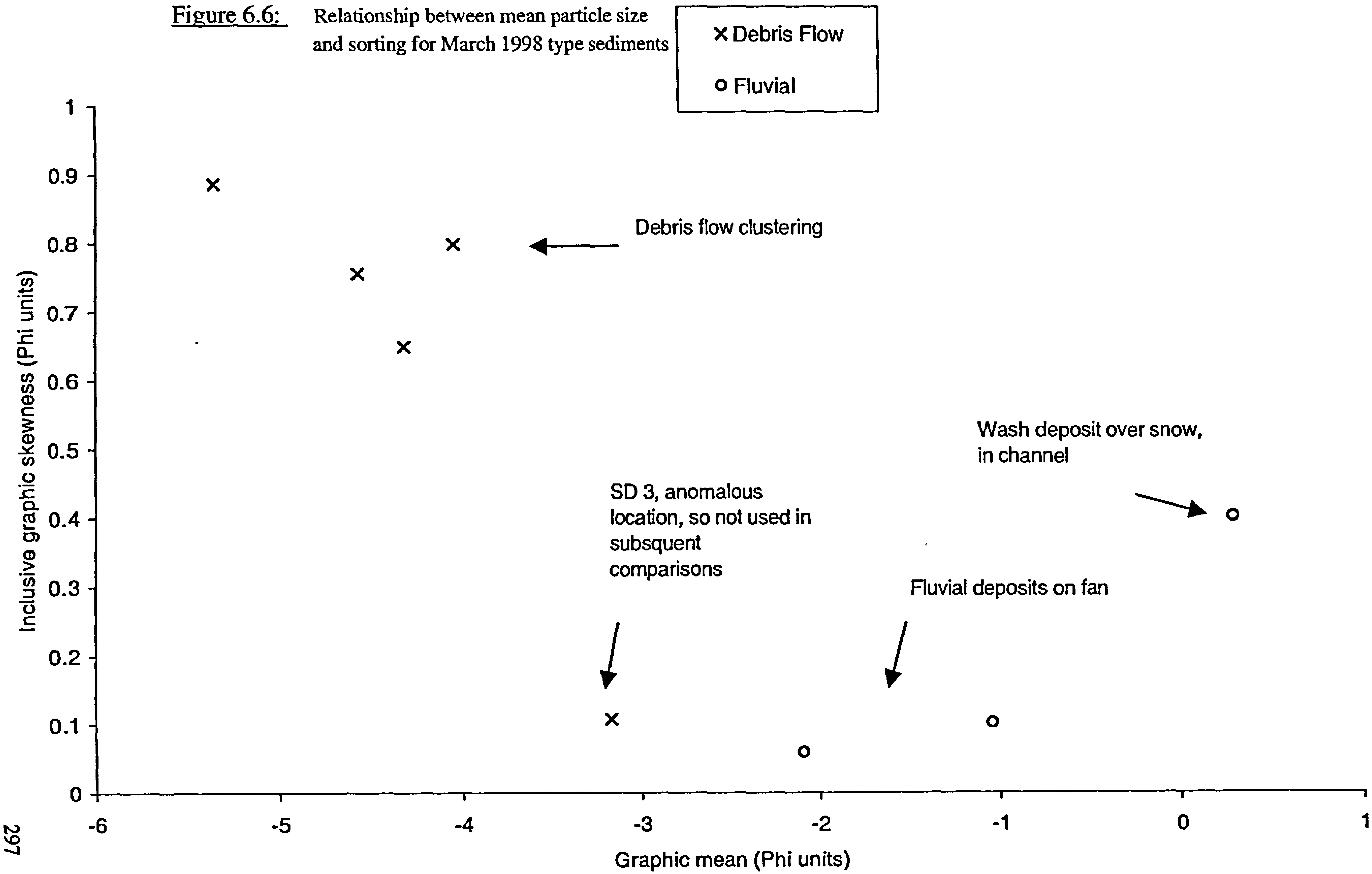
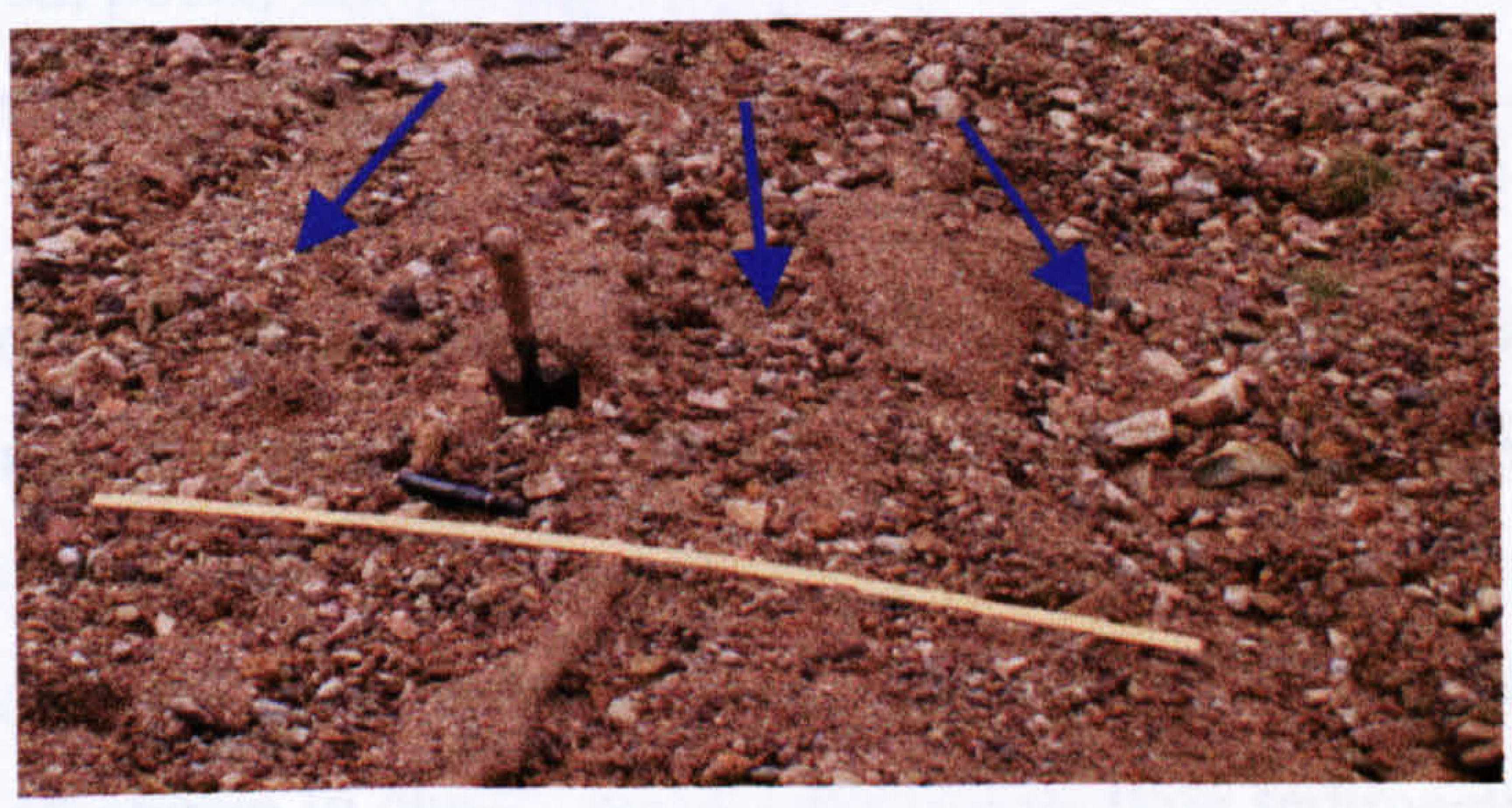


Figure 6.7: **Photographs of type deposits (13.3.98) with field sample codes. (Blue line shows flow direction).**

(A) Debris flow levee- SD 1

(B) Fan cone fluvial wash deposit- SD 5



(C) Right side of fan, wash deposit- SD 4

6.4.1.2 Pit sediments

A stratigraphic log was produced for the main pit sections. Each horizon in each pit sediment sequence was described and particle size characteristics were determined. This was undertaken for Pits 1, 2 and 3, but not Pit 4. Pit 4 could not be excavated more than 50 cm due to the local water table. The surface horizons in Pit 4 were dominated by vegetation and disturbed sediments, and it was therefore rejected as a reliable site at which to infer past fan process history. Figure 6.8 shows photographs of the three main pits and the vertical variability in sediment characteristics.

6.4.1.2.1 Pit 1 stratigraphy and sedimentology

Figure 6.9 illustrates the field stratigraphy and sedimentology of Pit 1. In this description sorting values are based on Compton (1962) who provides classification charts for sediments in five sorting categories, i.e. very well sorted, well sorted, moderately sorted, poorly sorted, and very poorly sorted. From this information three broad categories of sediment are identified: fluvial, debris flow, and fines.

Figure 6.10 shows the relationship between mean particle size and skewness for Pit 1 sediments and the type sediments. Horizons P1-2, P1-12 and P1-16 cluster around the debris flow type sediments, and are therefore considered as likely debris flow deposits. Horizons considered to be of fluvial origin (P1- 3, 5, 6, 7, 8, 10, 13, 14, 15, 17, 18, 19) are all shown to cluster around the fluvial type sediments. An additional fluvial deposit (P1-20) is identified on the basis of particle size analysis, although this was considered a clay horizon in the field. Particle size analysis demonstrated a granular deposit with a high silt/ clay content. The presence of finer material may reflect weathering breakdown of this basal deposit over time, or possibly leaching of clays from the upper profile. Horizons P1-4 and P1-9 were found to be clay rich in the field, and this fine fraction was confirmed by the particle size analysis. They both show smaller mean particle sizes (3.194 ϕ [0.11 mm] for P1-9; and 5.856 ϕ [0.02 mm] for P1-4), and are composed of high percentages of silt and clay sized particles, 47% for P1-6 and 74 % for P1-4 (Table 6.4).

Figure 6.8: Photographs showing exposures of the pit sediments. Clear layering and variability is evident. Poor drainage at the fan toe prevented deeper pit excavation

C. Pit One (30.6.98; 255cm depth)

A. Pit Two (16.9.98; 200cm depth)

B. Pit Three (15.9.98; 180cm depth)

Figure 6.9: Pit 1 field stratigraphy and sedimentology

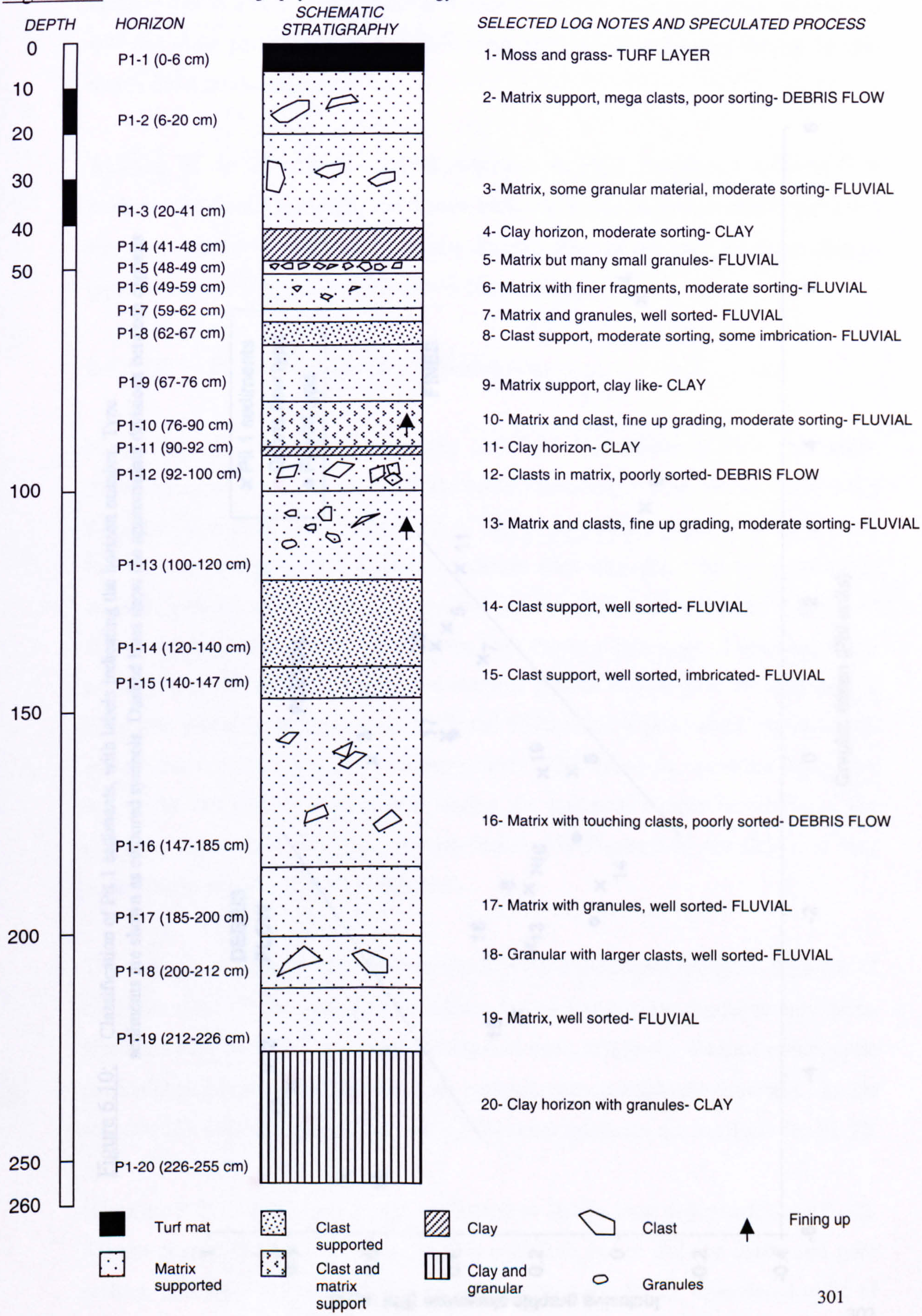
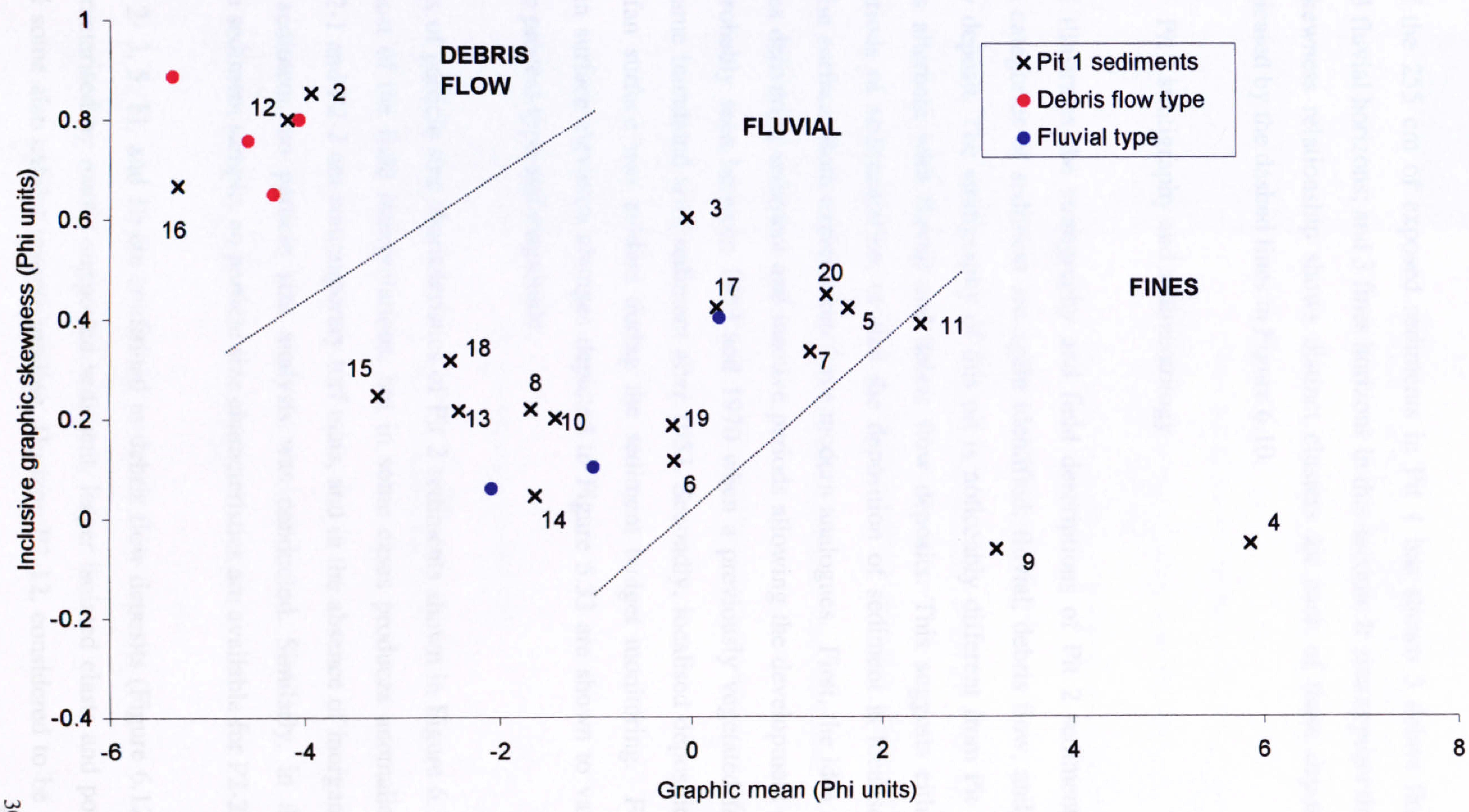


Figure 6.10: Classification of Pit 1 sediments, with labels indicating the horizon number. Type sediments are shown as coloured symbols. Dashed lines show the approximate divisions between deposits



On Figure 6.10 horizon P1-11 plots close to the fluvial group, but field observations identify this as a clay. The particle size analyses show a high percentage of sand and silt/ clay sized particles (50% and 32 % respectively) (Table 6.4) supporting the idea that is not a fluvial deposit.

Analysis of the 255 cm of exposed sediments in Pit 1 has shown 3 debris flow horizons; 13 fluvial horizons; and 3 fines horizons in this section. It also appears that the mean-skewness relationship shows distinct clusters for each of these deposit types as indicated by the dashed lines in Figure 6.10.

6.4.1.2.2 Pit 2 stratigraphy and sedimentology

Figure 6.11 illustrates the stratigraphy and field descriptions of Pit 2 sediments. Three main categories of sediment are again identified: fluvial, debris flow, and a finer clayey deposit. The stratigraphy of this pit is noticeably different from Pit 1. Finer layers alternate with fluvial and debris flow deposits. This suggests either episodic periods of sedimentation, or that the deposition of sediment is localised across the fan surface. Both explanations have modern analogues. First, the idea of active phases delivering sediment and inactive periods allowing the development of soils was probably seen between 1953 and 1970 when a previously vegetated fan surface became inundated with sediment after 1953. Secondly, localised deposition across the fan surface was evident during the sediment budget monitoring. For example, fan surface elevation changes depicted in Figure 5.33 are shown to vary according to process type and magnitude.

The analysis of particle size characteristics of Pit 2 sediments shown in Figure 6.12 confirms most of the field interpretations, but in some cases produces anomalies. Horizons P2-1 and P2-2 are contemporary turf mats, and in the absence of inorganic particulate sediment, no particle size analysis was conducted. Similarly, in the absence of a sediment sample, no particle size characteristics are available for P2-22.

Horizons P 2- 3, 5, 11, and 16 are confirmed as debris flow deposits (Figure 6.12). All are characterised by matrix-supported sediment, larger isolated clasts and poor sorting, and some also exhibit inverse grading. Horizon P2-12, considered to be of

Figure 6.11: Pit 2 field stratigraphy and sedimentology

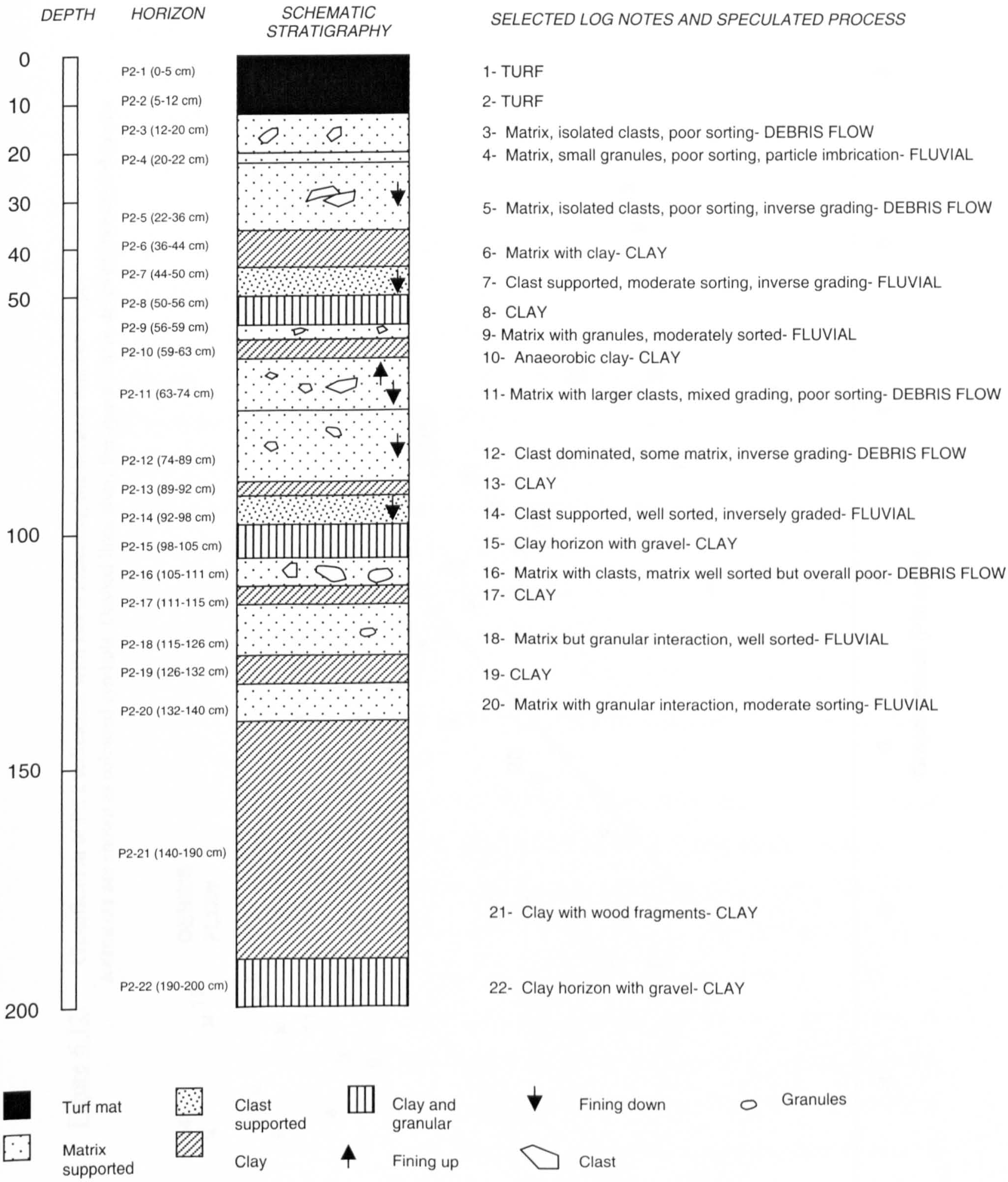
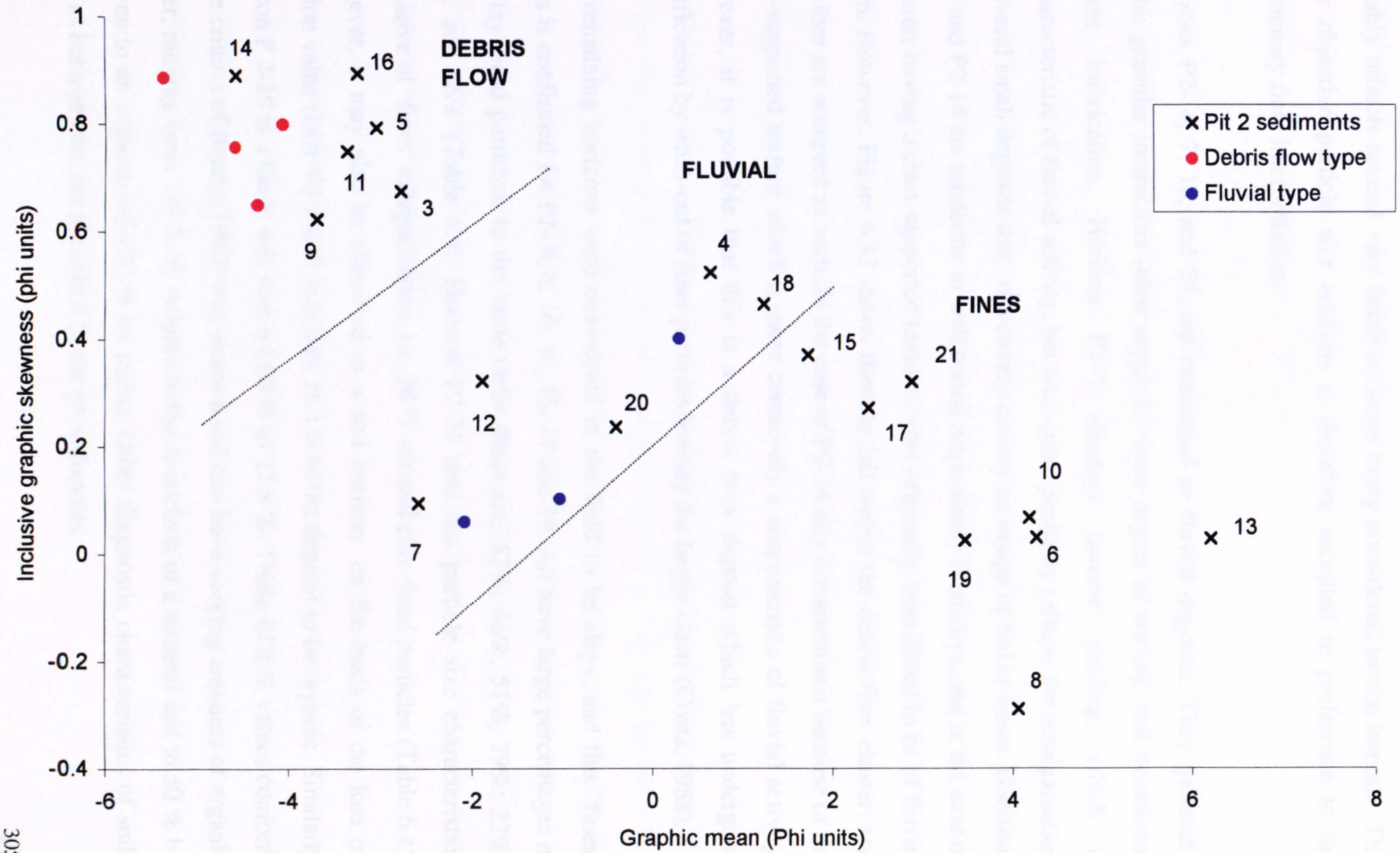


Figure 6.12: Classification of Pit 2 sediments, with labels indicating the horizon number. Type sediments are shown as coloured symbols. Dashed lines show the approximate divisions between deposits



debris flow origin on the basis of field observations is rejected as such by the particle size analysis. The sediments have a mean size of –1.9 ϕ (3.73 mm) and a skewness of 0.321 ϕ, and therefore are more likely to be of a fluvial origin (Table 6.4). The identified inverse grading (larger particles at top fining to smaller lower down) probably reflects several very small horizons being considered as one horizon. The more objective particle size analysis is therefore accepted in preference to the preliminary field interpretation.

Horizons P2- 4, 7, 18, and 20, are confirmed as fluvial deposits. They generally exhibit granular interaction (clast support), some degree of sorting, and occasional particle imbrication. Horizon P2–7 displays inverse grading, which is uncharacteristic of fluvial activity, but once more probably reflects the amalgamation of several small deposits that collectively convey an image of fining down. Horizons P2-9 and P2-14 are moderate to well sorted respectively (visually), and in the case of the latter having a clast supported texture, were originally considered to be of fluvial origin. However, Figure 6.12 shows them to fall within the debris flow cluster, and therefore are accepted as such. In the case of P2-14 this is contentious because of the clast-supported texture which is more commonly a characteristic of fluvial activity. However, it is possible that this is a debris flow deposit which has undergone modification by wash-out of finer particles leaving the larger clasts (Costa, 1988).

The remaining horizons were considered in the field to be clays, and this 'fines' status is confirmed for P2- 6, 8, 10, 13, 15, 17 and 19. All have large percentages of silt/clay sized particles, in the same order these are: 52%; 66%, 51%, 79%; 23%; 33%; and 46% (Table 6.4). Horizon P2-21 also has particle size characteristics indicative of 'fines' categorisation, i.e. 38 % silt and clay sized particles (Table 6.4). However, it may also be classified as a soil horizon, on the basis of the loss on ignition value (LOI %) which indicates 16.1% of the deposit to be organic. Similarly horizon P 2-19 is a likely soil with a LOI % of 27.8 %. These LOI % values conform to the criteria of Brady (1990) who states a soil can have varying amounts of organic matter, ranging from 1-6 % by volume in the A-horizon of a mineral soil to 50 % by volume in an organic soil (20 % by mass). Other diagnostic characteristics of soils such as horizons are not identified in the pit sediments.

After the variable correspondence between visual and particle size determinations of process type, the final classifications are those given in Figure 6.12. Hence, the reconstructions over 200 cm of deposit have shown 6 debris flow horizons, 5 fluvial horizons, and 8 fine horizons at this location, of which two are probably buried soils. As with Figure 6.10, distinct clusters in the mean-skewness relationship are visible.

6.4.1.2.3 Pit 3 stratigraphy and sedimentology

Figure 6.13 illustrates the stratigraphy and field sedimentology of Pit 3 sediments. The same three categories of sediment are again identifiable (fluvial, debris flow and fines).

Figure 6.14 suggests horizons P3-1 and P3-11 are of debris flow origin. The first is in agreement with field observations, but P3-11 was identified to be clast supported and well sorted deposit, i.e. typical of fluvial activity. As these field observations are so definite, they are selected in favour to the particle size analysis. All fluvial deposits classified in the field are confirmed to be this origin by particle size analysis. These include horizons P3- 2, 5, 7, 9, and 13.

Horizons P3- 6 and P3-8 in the field appear to be two thin buried soil layers. They have silt/ clay contents of 42% and 32% respectively (Table 6.4). The former is less organic with a LOI % of 6.6% and is therefore less likely to be a soil, whereas the latter is more organic with a LOI % of 19.1% (Table 6.4) and following Brady (1990) could be an organic soil horizon. Further to this the organic content of P3-8 is noticeably different to the organic contents of fluvial and debris flow deposits in Pit 3, which have LOI % values of 3% and 3.5% respectively.

The remaining horizons: P3- 10 and P3-12, were in the field considered clays, and given the high silt/ clay percentages established by particle analyses 86% and 68% respectively, these interpretations of fines stand. Further, given their high organic contents (P3-10: 26%; P3-12: 34%) (Table 6.4), they may also be soil horizons.

Figure 6.13: Pit 3 field stratigraphy and sedimentology

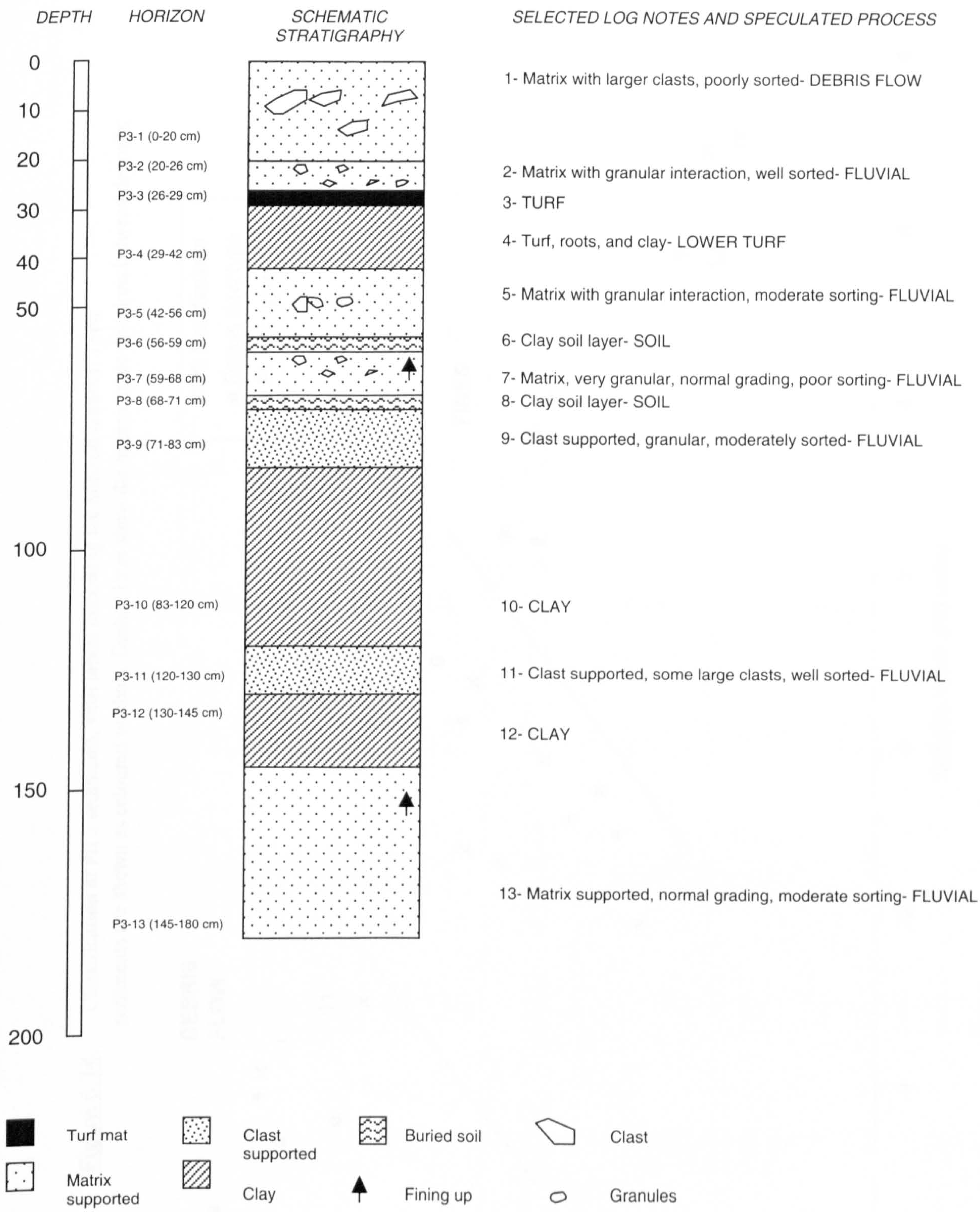


Figure 6.14: Classification of Pit 3 sediments, with labels indicating the horizon number. Type sediments are shown as coloured symbols. Dashed lines show the approximate divisions between deposits

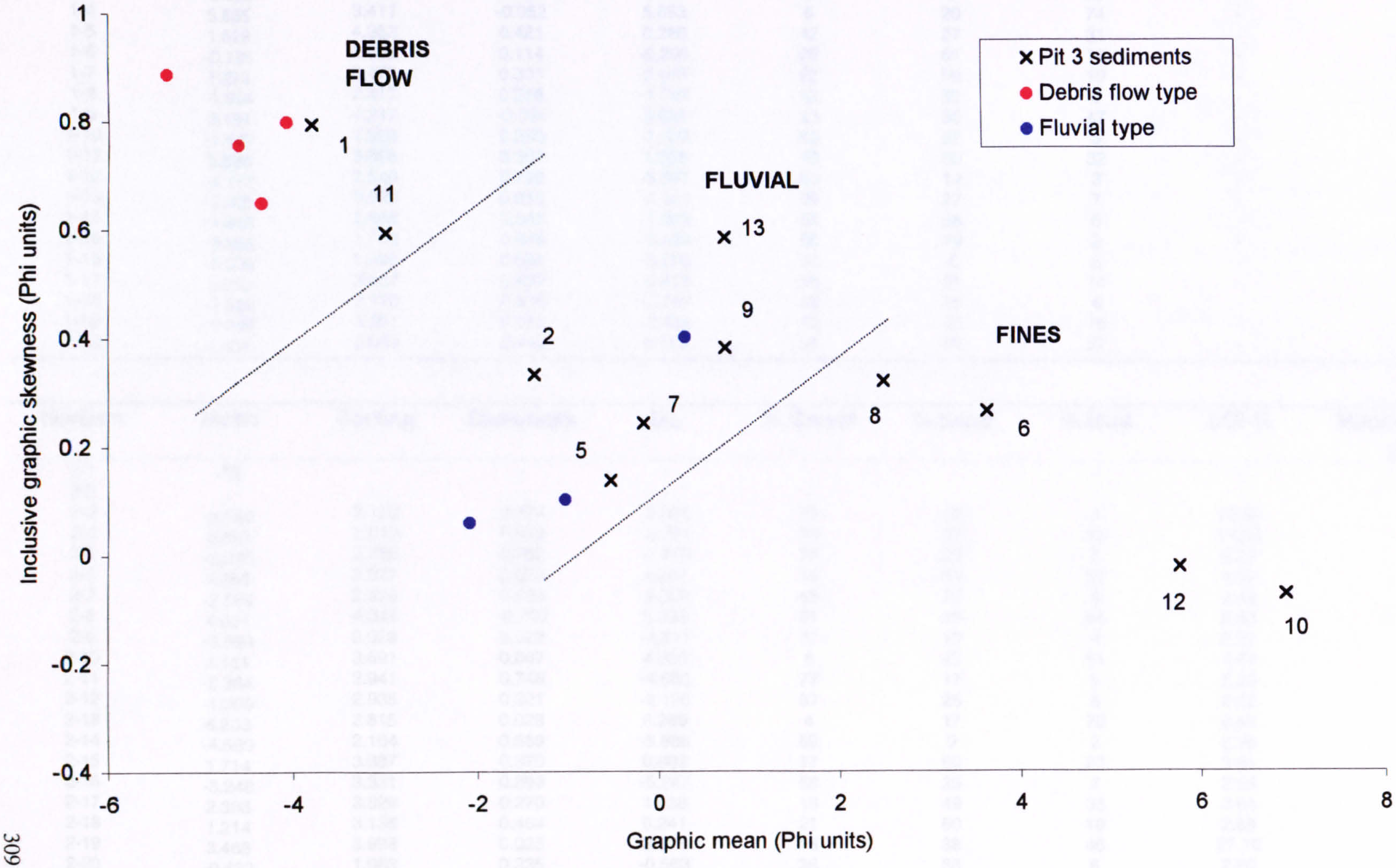


Table 6.4: Data series for pit sediments

Horizon	Mean	Sorting	Skewness	D_{50}	% Gravel	% Sand	% Mud	LOI % *2	Magnetic susceptibility χ lf (μ m^3 kg^{-1})
1-1	-*1	-	-	-	-	-	-	-	0.068
1-2	-3.934	2.161	0.851	-5.286	83	15	2	-	0.052
1-3	-0.056	4.730	0.601	-2.161	66	8	26	-	0.140
1-4	5.855	3.411	-0.052	5.853	6	20	74	-	0.123
1-5	1.629	4.353	0.421	0.286	42	27	31	-	0.064
1-6	-0.196	2.895	0.114	-0.200	29	61	10	-	0.068
1-7	1.223	3.476	0.333	0.486	22	59	19	-	0.064
1-8	-1.694	2.417	0.218	-1.747	62	32	6	-	0.110
1-9	3.194	4.217	-0.064	3.631	23	30	47	-	0.057
1-10	-1.442	1.964	0.200	-1.522	63	32	5	-	0.083
1-11	2.398	3.898	0.387	1.286	18	50	32	-	0.064
1-12	-4.172	2.540	0.799	-5.537	83	14	3	-	0.064
1-13	-2.435	3.096	0.215	-2.434	66	27	7	-	0.050
1-14	-1.643	2.648	0.045	-1.369	58	36	6	-	0.041
1-15	-3.268	1.730	0.246	-3.496	88	10	2	-	0.060
1-16	-5.309	1.490	0.665	-5.595	91	6	3	-	0.052
1-17	0.250	3.007	0.422	-0.475	35	51	14	-	0.049
1-18	-2.525	2.770	0.315	-2.762	68	26	6	-	0.073
1-19	-0.205	3.951	0.185	-0.439	42	42	16	-	0.050
1-20	1.401	3.603	0.448	0.119	21	58	21	-	0.040

Horizon	Mean	Sorting	Skewness	D_{50}	% Gravel	% Sand	% Mud	LOI %	Magnetic susceptibility χ lf (μ m^3 kg^{-1})
2-1	-*3	-	-	-	-	-	-	-	-
2-2	-	-	-	-	-	-	-	-	-
2-3	-2.780	3.120	0.674	-3.885	79	13	8	12.52	0.079
2-4	0.623	2.940	0.523	-0.291	33	52	15	14.05	0.059
2-5	-3.046	2.758	0.792	-4.419	75	20	5	2.22	0.064
2-6	4.260	3.827	0.030	4.207	14	34	52	4.82	0.093
2-7	-2.598	2.979	0.093	-2.300	68	26	6	2.48	0.114
2-8	4.061	4.348	-0.290	5.333	21	13	66	8.63	0.038
2-9	-3.693	2.928	0.622	-4.811	77	19	4	2.37	0.050
2-10	4.181	3.691	0.067	4.059	6	43	51	4.64	0.053
2-11	-3.364	2.941	0.748	-4.660	77	17	6	2.35	0.065
2-12	-1.900	2.935	0.321	-2.120	67	25	8	2.02	0.052
2-13	6.203	2.815	0.028	6.269	4	17	79	6.53	0.045
2-14	-4.569	2.164	0.889	-5.886	89	9	2	2.39	0.049
2-15	1.714	3.387	0.370	0.802	17	60	23	3.91	0.032
2-16	-3.248	3.331	0.893	-5.247	68	25	7	2.56	0.034
2-17	2.393	3.829	0.270	1.638	18	49	33	3.64	0.040
2-18	1.214	3.138	0.464	0.241	21	60	19	2.89	0.034
2-19	3.463	3.998	0.025	3.576	16	38	46	27.78	0.045
2-20	-0.422	1.983	0.235	-0.563	36	58	6	2.90	0.039
2-21	2.876	3.722	0.320	2.125	12	50	38	16.11	0.116

Table 6.4 cont.

Horizon	Mean	Sorting	Skewness	D_{50}	% Gravel	% Sand	% Mud	LOI %	Magnetic susceptibility χ lf (μ m^3 kg^{-1})
3-1	-3.786	2.479	0.794	-5.032	82	14	4	2.54	0.054
3-2	-1.388	2.883	0.332	-1.652	60	31	9	2.63	0.048
3-3	-*4	-	-	-	-	-	-	63.18	0.028
3-4	-	-	-	-	-	-	-	15.91	0.052
3-5	-0.537	4.166	0.137	-0.550	42	42	16	5.57	0.074
3-6	3.618	3.736	0.265	2.942	10	48	42	6.66	0.085
3-7	-0.180	3.126	0.243	-0.512	38	50	12	2.85	0.033
3-8	2.478	3.262	0.319	1.849	9	59	32	19.13	0.020
3-9	0.715	3.087	0.381	-0.040	27	57	16	2.49	0.031
3-10	6.921	2.655	-0.073	7.133	1	13	86	25.86	0.043
3-11	-2.999	3.123	0.593	-4.056	67	27	6	4.55	0.045
3-12	5.762	2.811	-0.022	6.034	3	29	68	33.75	0.032
3-13	0.717	2.735	0.584	-0.210	17	69	14	2.43	0.041

*1 = No particle size data for sample P1-1, as it is a contemporary turf layer and not a sedimentary deposit
*2 = No LOI % values for all Pit one sediments as samples processed without retaining raw sub sample which is required for LOI % testing.
*3 = No particle size/ LOI % data, as both P2- 1/2 are contemporary turf layers.
*4 = No particle size data for horizons P3- 3/4 as both are rich organic layers of low minerogenic composition.

As with Figures 6.10 and 6.12 the bivariate plot for Pit 3 (Figure 6.14) shows the clustering that has assisted with the identification of the process responsible for individual deposits. This reconstruction of depositional history at the distal end of the fan in a 180cm deep pit has identified one debris flow deposit, 6 fluvial deposits, and four fine horizons, of which three are probably buried soils.

Having reconstructed process history at three locations on the fan surface, issues of spatial variability need to be addressed. Table 6.5 shows the frequency of horizon types, their sum depth, and percentage depth of the total profile depth. Using these data a basic assessment of spatial changes can be made. Fluvial activity is seen to dominate at the fan apex (Pit 1) with 13 fluvial horizons (67 %), and similarly at the distal end of the fan (Pit 3) where 6 fluvial horizons occur (48 %). In Pit 2, debris flows (n= 6) are more numerous than at the two other pits, and are also greater than the number of fluvial horizons (n= 5). However, the percentage depth in Pit 2 made up of debris flow sediments is similar to Pit 1, where the actual depth is also greater as well. These preliminary findings may indicate that debris flow deposition is maximised in the centre of the fan, which possibly reflects a decline in flow energy with increasing distance from the fan apex, where flows emerge. On the other hand, there may be better preservation of debris flow deposits away from the apex, which is dominated by more frequent fluvial process activity, and hence is more likely to be disturbed. More detailed analysis of spatial differences require a temporal framework for pits to be established.

Table 6.5: Sediment type occupancy in Iron Crag fan pit profiles

Horizon process type	**Detail**	**Pit 1**	**Pit 2**	**Pit 3**
Debris Flow	Number horizons	3	6	1
	Sum depth (cm)	60	48	20
	% of profile	*24*	*24*	*11*
Fluvial	Number horizons	13	5	6
	Sum depth (cm)	171	42	86
	% of profile	*67*	*21*	*48*
Fines	Number horizons	3	8	4
	Sum depth (cm)	18	88	58
	% of profile	*7*	*44*	*32*

6.4.2 Temporal framework for the Iron Crag fan deposits

Palynology, magnetic susceptibility and radiocarbon dates have been used to reconstruct the longer-term chronological sequence of process activity at Iron Crag. Rates of process activity across the fan surface and throughout time are established, and causes of process activity have been investigated. Three widely cited causes of fan/ cone aggradation in the British uplands are considered: anthropogenic impact on the landscape, climate change, and extreme events (for example, Brazier and Ballantyne, 1989; Ballantyne, 1991b; McEwen, 1997; Ballantyne and Whittington, 1999).

6.4.2.1 Radiocarbon dates

Samples of material submitted for radiocarbon dating were obtained from Pits 2 and 3, namely horizons P2-19, P2-21, P3-6 and P3-12 (Figure 6.16 and Figure 6.17). These were considered of high dating potential as the horizons were relatively organic (LOI % values of: 27.8, 16.1, 6.6, and 33.8 respectively (Table 6.4)), and also in the case of P2-21 and P3-12 contained woody macro fossils. No sediment extracted from Pit 1 appeared sufficiently organic to permit dating.

The resulting radiocarbon dates (Table 6.6) are presented in radiocarbon years before present (AD 1950) and are also converted into calendar years using dendro-calibration methods outlined by Stuiver and Pearson (1993). In Pit 2 dates SRR-6599 (1260 AD) and SRR 6600 (1225 AD) are similar, and the calendar age ranges (± 1 total standard deviation) are shown to overlap (Table 6.6). The older date is obtained from a wood fragment which is visible in Figure 6.8 at 170 cm in the profile. If the best estimates of the age are considered accurate, then during a 35-year period (1225 to 1260 AD) a rapid development of soil occurred (see section 6.4.1.2.2 for discussion of soils), interrupted only briefly by the fluvial deposit of P2-20. Taking an average depth in horizon P2-19 of 129 cm for the upper dated unit, then over the 35-year period 41 cm of accretion occurred, which is an average of 11.7 mm per year. The wood fragment in horizon P2-21 is considered to be contemporary with the developing soil, and not an older in wash deposit. If it were of non-contemporary age, then the difference between SRR-6600 and the younger SRR-6599 higher up the profile would probably be greater. These two dates illustrate that the majority of coarse minerogenic sedimentation (debris flow/ fluvial) occurred following 1260 AD at Pit 2. This is, of course, constrained by the fact that horizon P2-22 is not the base of the fan deposits but simply the base of the excavation.

Pit 3 at the distal end of the fan is shallower, and contains three dates from two horizons. The youngest date SRR-6601 is obtained from horizon P3-6, and is calculated to be 1420 AD (± 20 years). Significantly older dates were obtained from horizon P3-12 i.e. SRR-6602 (36 BC) and AA-39694 (160BC). SRR-6602 is a date based on a bulk sample of the fibrous matrix of P3-12 obtained using a conventional dating approach, whilst AA-39694 is a date from a small wood fragment within the sample. This date was obtained using accelerator mass spectrometry (AMS), at Tuscon, Arizona. The difference in age between the two samples (best estimate = 124 years) whilst potentially within error margins, is more likely to signify that the wood fragment is of older age and is therefore an in-wash deposit. Hence SRR-6602 is considered a better best estimate of the age of horizon P3-12. This basal age cannot be taken to indicate the earliest phase of fan aggradation at Iron Crag, as this dated horizon is underlain by a fluvial deposit (P3 –13). Furthermore this confirms that the Pit 2 sediments do not represent the entire depositional sequence of the fan, because shallower deposits in Pit 3 (P3-12- max. 145 cm) are of older age than deeper deposits in Pit 2, i.e. P2-21- 170 cm. Hence deeper sediments would be expected in Pit 2.

The age difference between P3-6 and P3-12 using best estimates of age is 1456 calendar years. Over this timespan the stratigraphy is dominated by horizon P3-10, which is classified previously as 'fines', and therefore over this time period the base of the fan appears to have been largely inactive, or was possibly locally ponded leading to fine material deposition. It is only after P3-10 that coarse minerogenic activity is seen more frequently, with two fluvial deposits (P3-7, P3-9) being interrupted by soil formation at P3-8 (Figure 6.16, and section 6.4.1.2.3 for discussion of soils).

Table 6.6: Radiocarbon dating results obtained from the NERC Radiocarbon Laboratory and calculated calendar ages
[σ^s= sample standard deviation, σ^t= total standard deviation, given by Stuiver and Pearson (1993) to be $((\sigma^s)^2 + (\sigma^{curve})^2)^{0.5}$]

Publication code	Sample identifier	Dating Laboratory Description	Conventional Radiocarbon age (years BP ± 1 σ^s)	Calendar Age (year AD/ BC)	Calendar age +1 σ^t (year AD/ BC)	Calendar age -1 σ^t (year AD/ BC)
SRR-6599	P2-19 (126-132 cm)	Clay/ fibrous material	800 ± 45	1260 AD	1220 AD	1285 AD
SRR-6600	P2-21 (170 cm)	Wood	845 ± 55	1225 AD	1160 AD	1275 AD
SRR-6601	P3-6 (56-59 cm)	Clay/ sand	515 ± 55	1420 AD	1400 AD	1440 AD
SRR-6602	P3-12 (130-145 cm)	Fibrous material/ soil	2035 ± 40	36 BC	65 BC	20 AD
AA- 39694	P3-12 (130-145 cm)	Wood	2120 ± 46	160 BC	195 BC	45 BC

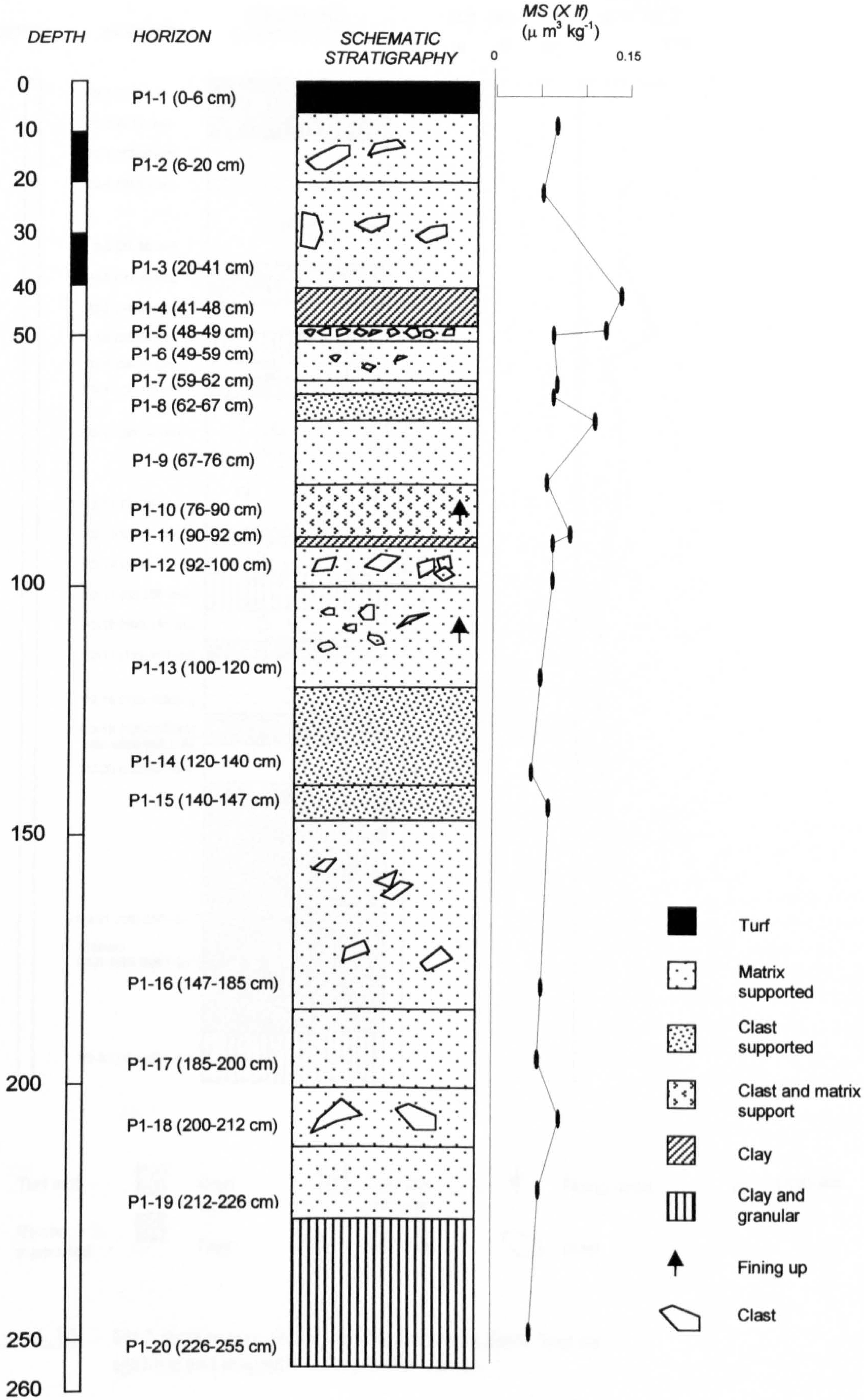


Figure 6.15: Pit 1 stratigraphy, inclusive of magnetic susceptibility values.

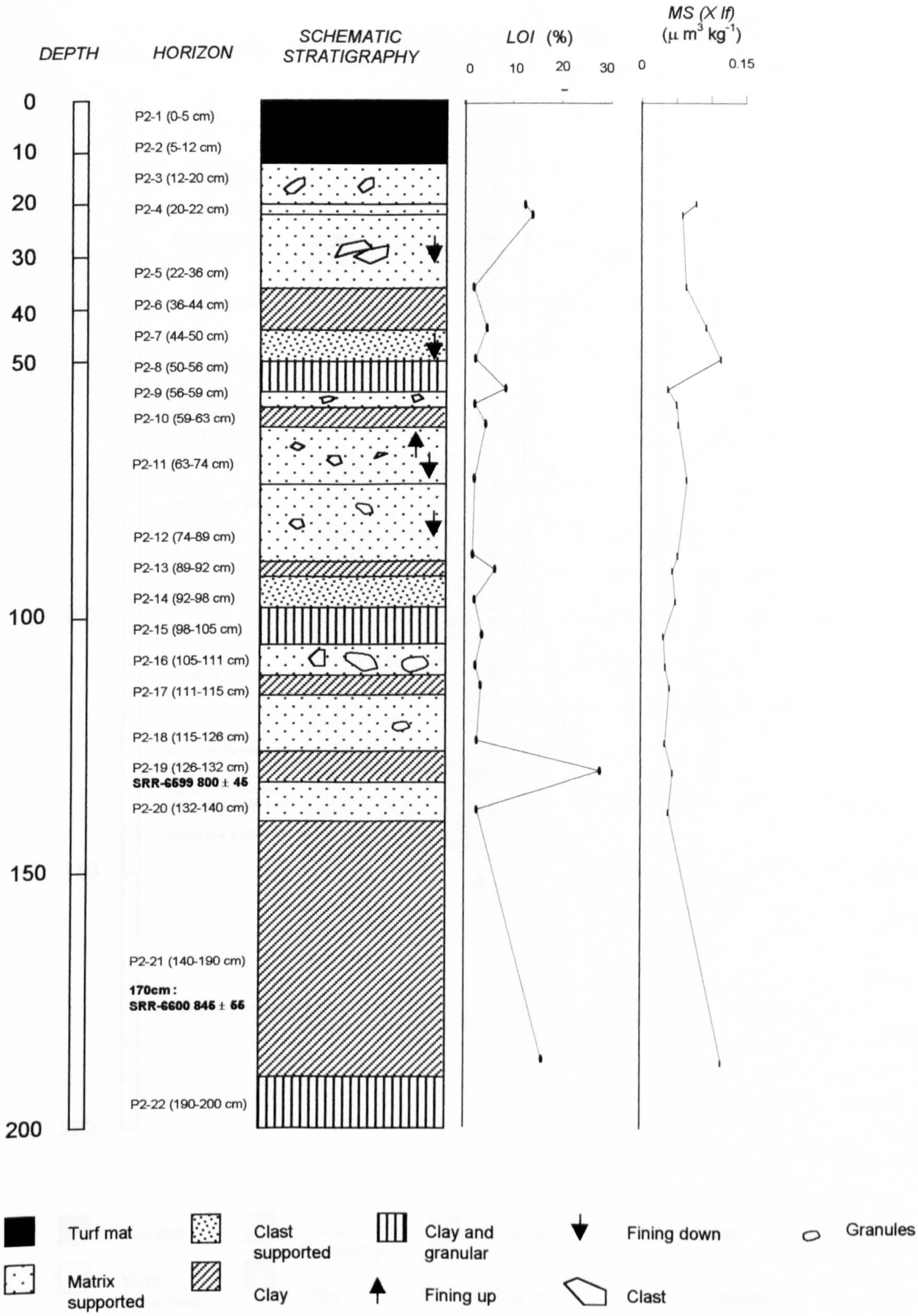


Figure 6.16: Pit 2 stratigraphy, inclusive of radiocarbon dates, loss on ignition and magnetic susceptibility values.

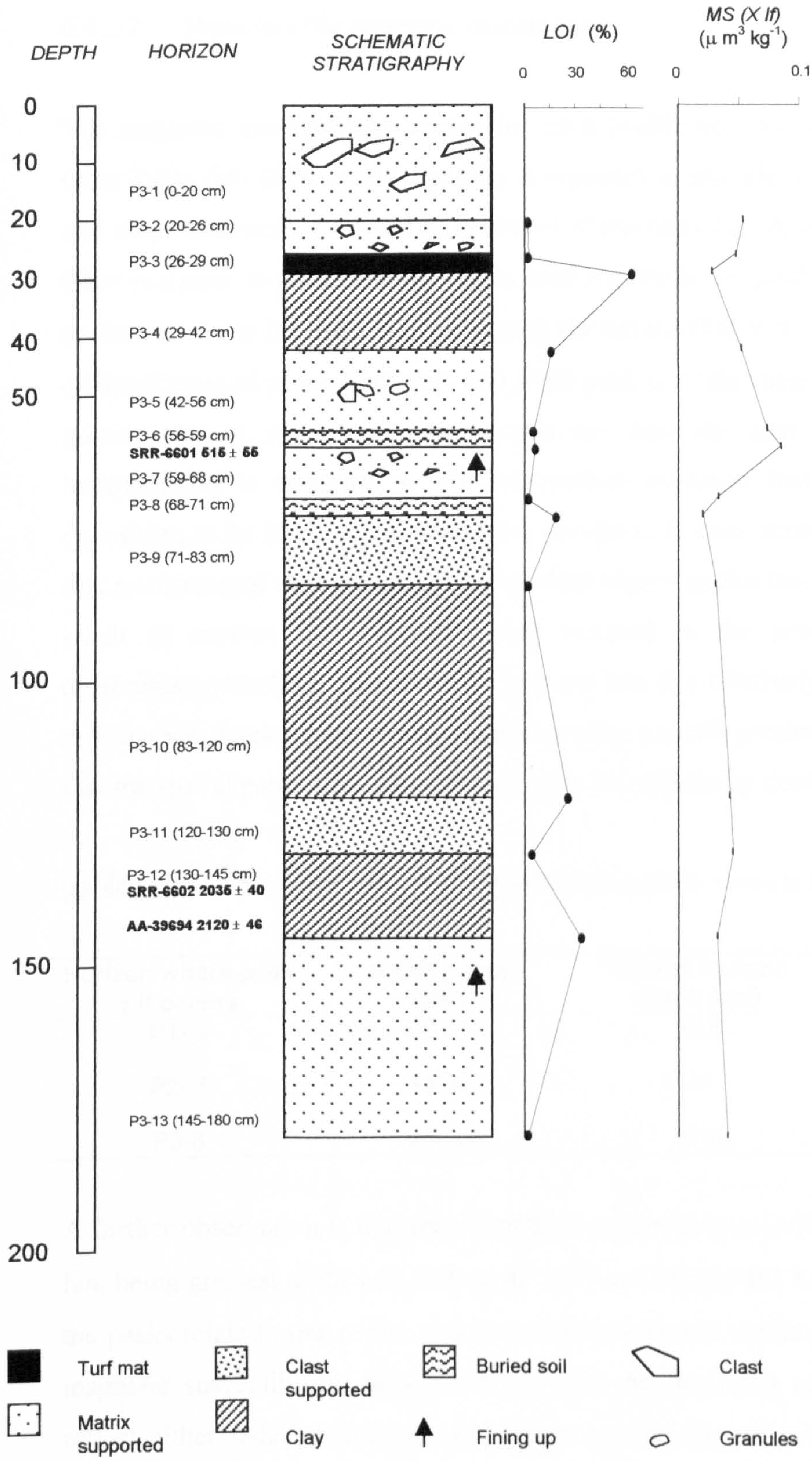


Figure 6.17: Pit 3 stratigraphy, inclusive of radiocarbon dates, loss on ignition and magnetic susceptibility values

6.4.2.2 Mass specific magnetic susceptibility

The magnetic susceptibility curves for each profile are shown in Figures 6.15-17 (also Table 6.4) (NB. pit stratigraphy is repeated to provide a setting for these data and other laboratory analyses of sediment characteristics). A common feature in all these is a peak in susceptibility values near the top of the profile. The peak depth is shallowest at the fan apex, and greatest at the fan toe (Table 6.7). This could indicate different rates of process activity, and if the peak is of the same age it would imply a greater rate of aggradation at the fan toe than the apex. However, such an interpretation is contrary to the radiocarbon evidence that generally indicates deposition to be more active nearer the fan apex. A more probable interpretation is that reworking of sediment is more prevalent higher up the fan, and therefore the net result of erosion and deposition has resulted in the peak being nearer the contemporary surface. Alternatively, because this is a relatively shallow feature and radiocarbon dates represent sedimentation over a much greater depth, it is possible that the spatial pattern of sedimentation may be variable by depth.

Table 6.7: Maximum mass specific magnetic susceptibility values in Iron Crag pit sediments

Horizon where peak χ lf occurs	Depth range (cm)	Central horizon depth (cm)	χ lf (μ m^3 kg^{-1})
P1- 3	20-41	30.5	0.1396
P2- 7	44-50	47	0.1138
P3-6	56-59	57.5	0.0851

A further observation is that the strength of magnetic susceptibility decreases down fan, being greatest at Pit 1 (0.1396 μ m^3 kg^{-1}) and least at Pit 3 (0.0851 μ m^3 kg^{-1}). If the peaks relate to one event, or a common time period yielding a mineral of higher magnetic susceptibility, then it follows that the declining magnetic signal could reflect either reduced sediment deposition or a sorting of sediment down the fan surface. This assertion corresponds to the earlier suggestion that coarse minerogenic process activity is more active at the head of the fan. Further, it is possible that this down-fan reduction in susceptibility peak is a signal showing the input of mining related sediment at or above the fan apex.

The magnetic susceptibility peak associated with P3-6, corresponds with radiocarbon date SRR-6601 (515 ± 55 ^{14}C years BP, 1420 ± 20 AD) which was obtained from the same soil horizon (Figure 6.17). This offers an opportunity to test the hypothesis that the peak in magnetic susceptibility is related to mining activity. Shaw (1970) states that the Caldbeck mines may have been worked in the 12th Century, and the Silver Gill mine is referred to in a 14th Century Charter. Cooper and Stanley (1990) indicate that the Duke of Northumberland had a mine supervisor for the Skiddaw area in 1453. Hence fragmentary evidence exists to suggest some mining activity around the age of the magnetic susceptibility peak, but this is too vague to be directly associated with process activity at Iron Crag. It is not until the early 19th Century that there is direct evidence of mining activity at Iron Crag, specifically the sinking of Lainton's Engine shaft after 1865 (Adams, 1988; Cooper and Stanley, 1990).

An additional value of the dated peak is that, if all similar peaks are assumed to be correlated, then it is possible by proxy to apply the SRR-6601 date to the horizons associated with the peaks in Pits 1 and 2. This provides a further method of calculating process rates on the fan surface.

6.4.2.3 Pollen data

Pollen was extracted from selected horizons in Pit 2 and 3. In Pit 2 units 6, 19, and 21, and in Pit 3 units 4, 6, 10, 11, and 12, were selected prior to LOI % testing and particle size analysis. These horizons appeared to be more organic and hence were likely to be soils that represent a more stable environment than coarse minerogenic horizons for pollen accumulation. Subsequent particle size analyses (sub section-6.4.1) confirm all sediments to be fines, except P3-11 that is a finer fluvial deposit.

The pollen diagrams constructed from this limited data are shown as Figures 6.18 and 6.19. These are constructed using TILIA software (Grimm, 1991), and display data in percentage form. The abundance of pollen or spore taxon is expressed as a percentage of the total pollen sum. In all but one case total pollen sums exceed 300 pollen grains. The data are plotted at the deepest depth of their parent horizon.

Figure 6.18: Iron Crag Pit 2 Pollen assemblage (% TP)

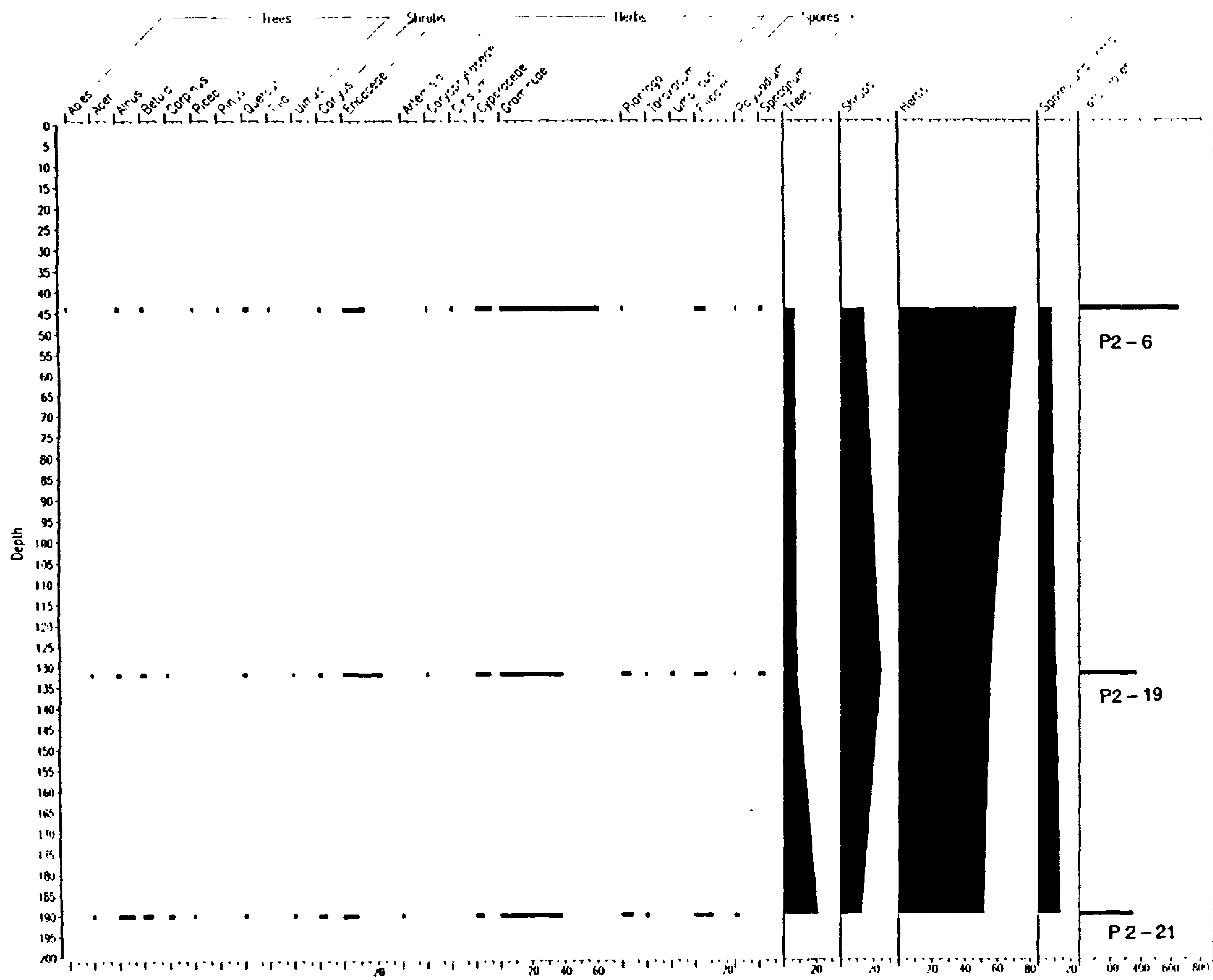
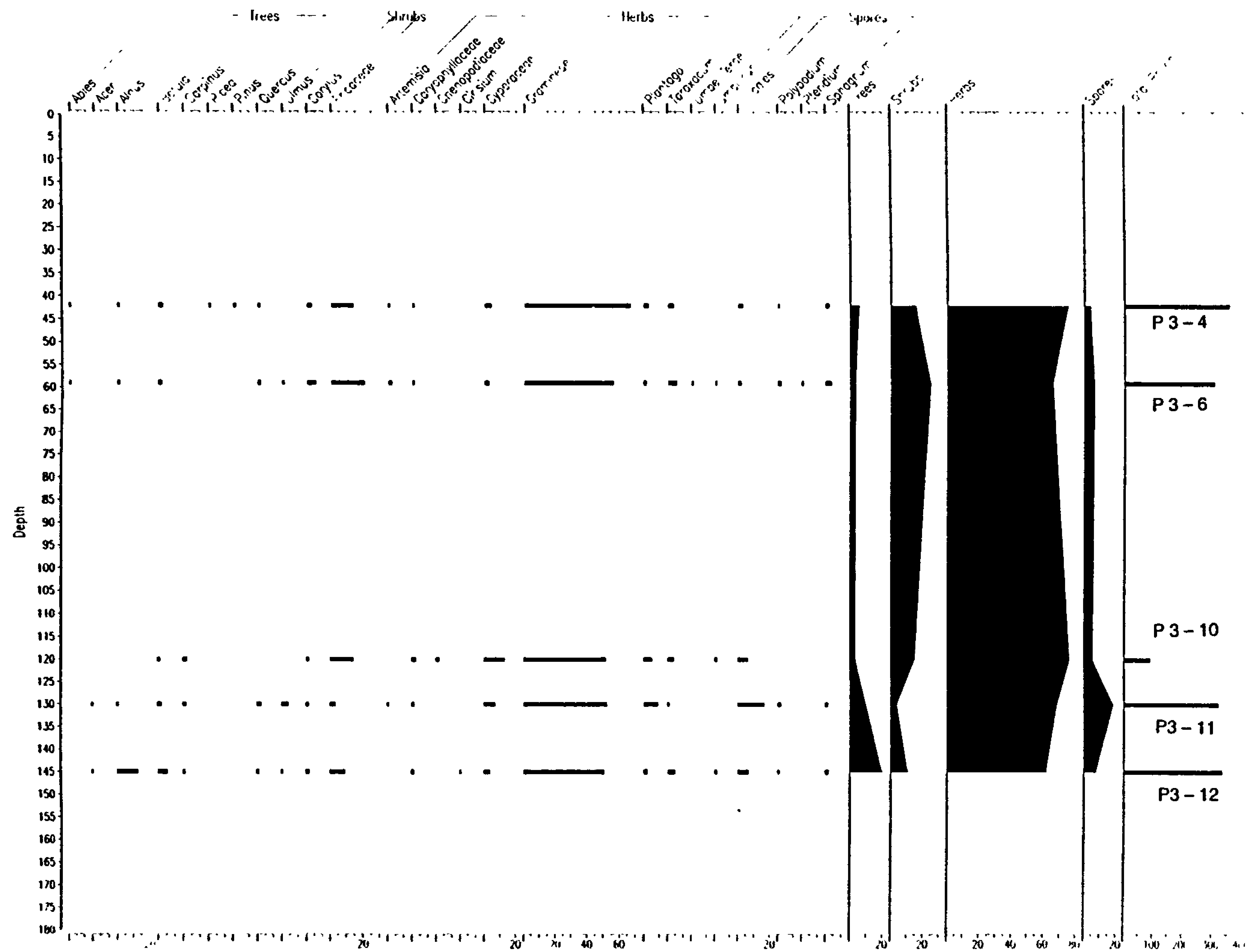


Figure 6.19: Iron Crag Pit 3 Pollen assemblage (% TP)



In most cases the depth range of the sediment horizon is small so this practice results in pollen data being near their true depth. Pit 2-21 has the largest vertical range of 50 cm, but the sediment was sampled between 170 cm and 190 cm.

With regard to the Pit 2 pollen sequence (Figure 6.18) it is seen that all horizons are dominated by non-arboreal pollen, particularly *Gramineae* (38.0-60.8 %) *Cyperaceae* (4.6-9.5 %). Of the tree species *Alnus* (1.7- 9.5 %) and *Betula* (1.3-5.5 %) are largely dominant, although *Quercus* is the most dominant tree species (2.7 %) in horizon P2-6. *Ericaceae* is a strong contributor to the total pollen sum, ranging between 8.4 % and 22.5 %, and shows a noticeable increase between horizons P2-21 and P2-19. Coincident with this increase in shrubs (12.97% to 24.66 %) is a decline in the total proportion of tree pollen (21.33 % at P2-21 to 8.22% at P2-19), most particularly *Alnus*. Radiocarbon dates SRR-6600 (170cm) and SRR-6599 (126-132 cm) place this decline in trees and increase in moorland heath vegetation (*Ericaceae*) to have begun at the latest by 1225 AD (best estimate, age range 1160 AD to 1275 AD). These observations are similar to changes occurring at Coniston Water (Pennington, 1997) (40 km south of Iron Crag), where the final phase of tree clearance once again including *Alnus* (c. 1000 AD) gave way to dwarf shrub heath, especially *Calluna*.

The cultural indicators *Plantago* (Plantain family) and *Artemisia* (Mugworts and wormwoods) (Brazier *et al.*, 1988; Anderson and Parker, 1997) are both evident at P2-21, with percentages of 0.86% and 6.63% respectively. The presence of these species indicates the existence of clearance episodes prior to the arboreal decline identified at P2-19, although the continued presence of *Plantago* at P2-19 (5.21 %) suggests sustained disturbance of the landscape. Finally, by P2-6 a decline in heath (*Ericaceae*) and increase of *Gramineae* relative to the P2-19 contributions is observed. Pennington (1997) remarks that this transition occurred by mediaeval times and is consistent with a long documented history of sheep farming in the region.

Figure 6.19 illustrates the pollen sequence derived from 5 horizons at Pit 3. As with Pit 2, non-arboreal species dominate the pollen diagram, particularly *Gramineae* (50.0-66.2 %), *Cyperaceae* (2.0-12.5 %) and *Plantago* (0.7-8.5 %). Of the tree species *Alnus* is dominant at P3-12 (12.65 %), though thereafter *Betula* is most often the dominant tree pollen, attaining a maximum contribution of 2.0 %. *Ericaceae* is an important species; whilst initially showing a decline between P3-12 and P3-11, thereafter it increases peaking in P3-6 at 20.1 %, and shows its greatest rate of increase between P3-11 and P3-10, 2.8 % and 13.6 % respectively. This is nearly a five times increase, whereas the increase between P3-10 and P3-6 is only a 1.5 times change. As with Pit 2 the initial increase in *Ericaceae* between P3-11 and P3-10 corresponds to a decline in the total proportion of tree pollen (9.72 % to 3.41%).

Radiocarbon dates AA-39694 and SRR-6602 correspond to horizon P3-12, though as already stated, the AMS date is probably less representative. Hence SRR-6602 can be used to date the greater arboreal presence at P3-12 to 36 BC (best estimate, age range 65 BC to 20 AD). Following this, an increase in *Plantago*, *Artemisia,* and *Ericaceae* all support the observed clearance culminating in the low tree proportion at P3-10. An important question is whether this clearance phase, as with the one observed in Pit 2, corresponds with the final phase of regional clearance in the Lake District (c. 1000 AD). Alternatively, given the older radiocarbon dates from Pit 3, whether it reflects evidence of an earlier clearance, i.e. Romano-British or the third main phase at 700-800 AD (Pennington, 1997). Given the poor vertical resolution of the P3-10 pollen evidence it is possible that it is in reality nearer P3-6 (dated with SRR-6601 to 1420 AD) than depicted on Figure 6.19. It is tempting to suggest that this vegetation clearance is of the same age as the post 1000 AD episode in Pit 2; however, no evidence exists to substantiate this.

SRR 6601 dates the *Ericaceae* and *Artemisia* maxima to 1420 AD (best estimate, age range 1400-1440 AD). An increase in *Gramineae* and decline in *Plantago* accompany this change. This increase in heath and grassland at this time follows the expansion of sheep farming by Cistercian monasteries in the 13th century (Pearsall and Pennington, 1973.) This horizon (P3-6) is chronologically coincident with the formation of peat at Mosedale Beck (NY 354 232), 12 km south east of Iron Crag. Here date Beta-102303 (570 ± 100 BP, 1400 AD) confirms herbs and shrubs to again be dominant contributors to the total land pollen sum, and is once more synchronous with Middle Age sheep farming (Anderson and Parker, 1997).

6.4.2.4 Synthesis of evidence: the cause of historical erosion at Iron Crag

Radiocarbon dates (Table 6.6) provide the primary source of evidence for the ages of process activity on the Iron Crag fan. By association with magnetostratigraphy and pollen stratigraphy, further proxy dates can be applied to the pit sediment sequences, from which interpretations about the causes of fan deposition can be suggested.

Pit 3-12 (36 BC) is shown to be oldest dated horizon on the Iron Crag fan, although as already stated this cannot be taken to represent a minimum age for the initiation of process activity because the underlying deposit (P3-13) is of fluvial origin. In the deposits exposed by the excavations, the most noticeable coarse minerogenic deposition is between P2-19 and P2-7; and P3-9 to P3-5. In the case of Pit 2, horizon P2-19 is 1260 AD, and P2-7 corresponds to the magnetic susceptibility peak dated in Pit 3 to 1420 AD; so by proxy P2-7 is considered of similar age, whilst the P3 coarse minerogenic phase deposits occur just prior to P3-6 (1420 AD). Both pits therefore suggest a timeframe of a few hundred years for a phase of fan aggradation.

The pollen evidence in Pit 2 and possibly Pit 3 show a decline in trees and increase in heath and grasslands that are coincident with land clearance by Cistercian monks. Pearsall and Pennington (1973, p252) state:

"The Cistercians were farmers and wool merchants on a very large scale. Their conversion of large tracts of fell country, much of it at the time probably still wooded to some extent, into sheep pasture, must have changed the vegetation but also the animal communities."

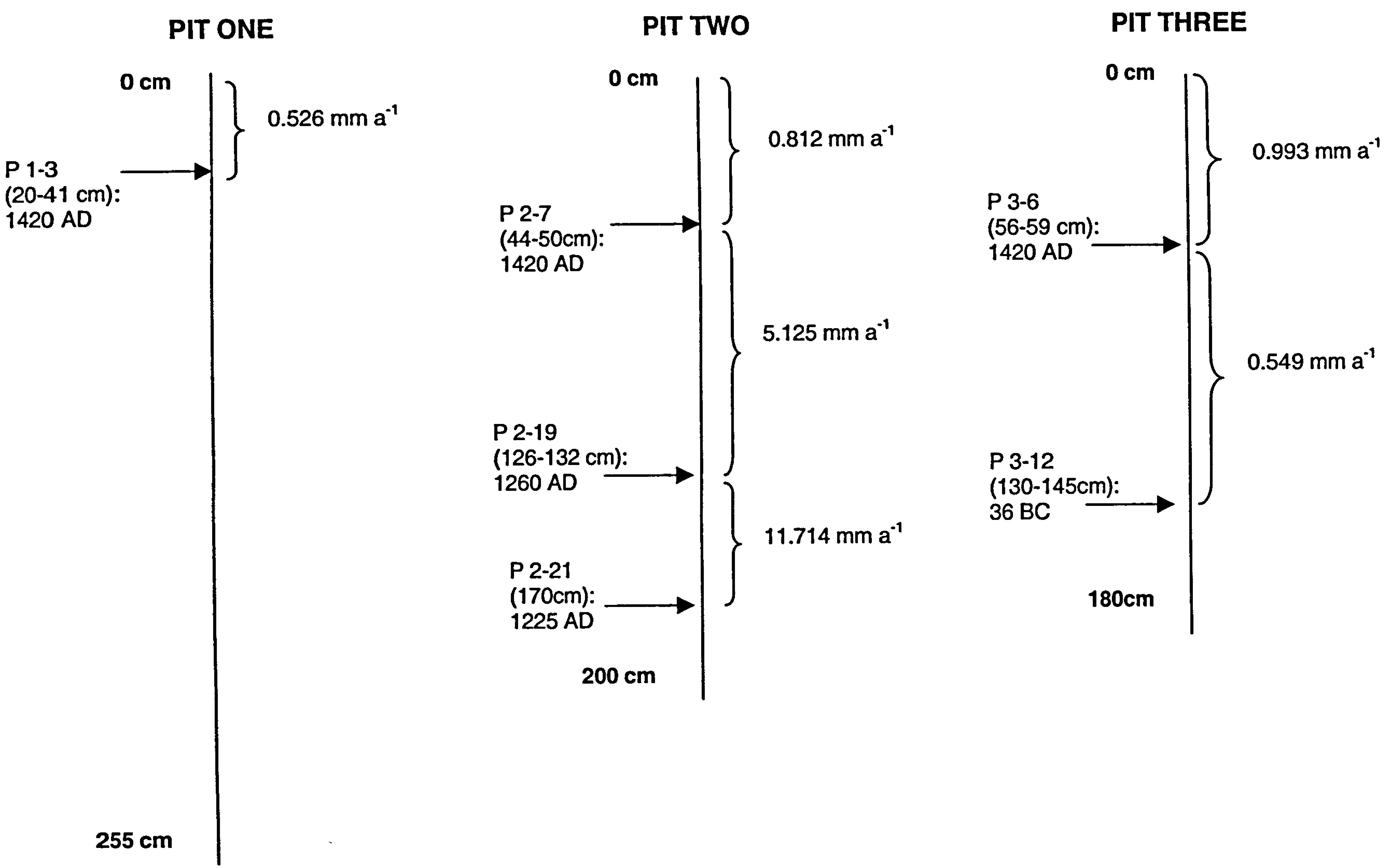
Such evidence suggests that the deforestation of the Lake District Fells is probably responsible for the renewed erosion and deposition of the Iron Crag system in the Middle Ages.

Climatic changes were also occurring during the Middle Ages. Lamb (1977) noted that between 1000 AD and 1200 AD the medieval warm epoch (Little Optimum) prevailed. This was characterised by a high frequency of dry summers and mild, and at worst, moderate winters. Pennington (1997) states such conditions would allow hardy local breeds of sheep to persist on the fells. A 'climatic worsening' in the late Middle Ages (c. 1200-1400 AD) brought increased wetness and colder temperatures to temperate Europe (Lamb, 1977). It is therefore possible that the previous clearance of woodland occurring under opportune climatic conditions removed protective vegetative cover increasing the sensitivity of the ground to erosion. This erosion at Iron Crag between 1200 and 1400 AD may well be a reflection of the harsher climatic conditions at this time, though as argued by Ballantyne (1991b) this association of cause and effect is only founded on a coincidence of timing based on approximate dates, without association to any particular change. Therefore this appears to be a weaker explanation than anthropogenic disturbance that has support from palynological evidence. However, the observation that many fine horizons (including soils) separate coarse minerogenic deposits tends to suggest phases of activity and stability. Following Ballantyne and Whittington (1999) this could be interpreted as evidence of the impact of single storm events. Hence the fan aggradation of Iron Crag during the Middle Ages may owe its origin to a combination of all three formative hypotheses, though primarily its initiation relates to human impact on the landscape.

6.4.2.5 Process rates

Figure 6.20 shows the variability of rates of fan deposition in each of the three pit profiles. The depth used in the calculation is the centre point of the horizon. The most active phases of deposition are recorded in Pit 2. As previously noted, between 1225 AD and 1260 AD (average rate of 11.7 mm a^{-1}), and between 1260 AD and 1420 AD (5.1 mm a^{-1}). The only other pre-1420 AD rate calculated is for Pit 3 between 36 BC and 1420 AD (0.55 mm a^{-1}). This lower rate is a reflection of the longer time period, which is considered to encompass a prolonged phase of stability. Following 1420 AD the rate of fan deposition is again less, ranging from 0.53 mm a^{-1} to 0.99 mm a^{-1}. Noticeably the greatest of these surface rates is at the fan toe (Pit 3), but as already noted this is misleading and probably reflects less fluvial disturbance of the surface sediment at Pit 3, therefore leaving a greater accumulation of material after the main magnetic susceptibility peak. The temporal frequency of fluvial and debris flow activity at Pit 2 is also shown to be greater during the 1260-1420 AD time period than that occurring after 1420 AD. This indicates the

Figure 6.20: Schematic diagram showing the age control and estimated sedimentation rates (mean annual aggradation rates) for the three Pit sections at Iron Crag. Horizons are plotted at their mean depths.



occurrence of abundant material and suitable flow conditions during this period. Rates calculated in this manner are highly dependent on the frequency of dates and the degree of continuity of the sedimentary record. In this example dates are too few and rates of sedimentation too episodic for many clear conclusions to be drawn.

6.4.3 Comparison of Iron Crag fan history to other fan chronologies

Table 6.8 lists details of aggradational phases in fans and debris cones in the British Uplands. It indicates the timing of initial fan aggradation and subsequent reactivation(s), and also reports the inferred causes of coarse minerogenic deposition. A consistent timing for the first dated phases of aggradation occur around 2000 ^{14}C BP (Glen Feshie, Edendon Valley, Fiendsdale fan, Little Harden fan, and Iron Crag), and in some cases this is attributed to both high magnitude events and Bronze Age/ Iron Age human settlement. Following Dunsford (1998) it is apparent that a second phase of aggradation also occurs around 900 ^{14}C BP (Edendon Valley, Dry Cleugh, Thickcombs Gill, Caste fan, and probably the Seathwaite fan). These are dominantly considered to be related to land clearance and sheep grazing associated with later Viking settlement.

The reactivation at Iron Crag occurs a little later after 845 ± 55 ^{14}C BP, and is therefore considered not to reflect a response to Viking settlement, but instead deforestation and sheep grazing associated with the later Monastic period. Furthermore, particular storm events may be responsible for the rapid deposition (Ballantyne and Whittington, 1999), for example in Pit 2. Unlike the Edendon valley, evidence of anthropogenic disturbance is also apparent in the Iron Crag deposits. The hypothesis of historical storm-related sediment pulses at Iron Crag is consistent with current process activity at the site that is significantly enhanced during storm periods (Chapter 5). Further to this, the medium-term history reconstructed earlier in this chapter supports a model of event-controlled fan deposition. The radiocarbon dating of aggradation at Iron Crag provides the first such result for the Lake District, and is found to have similarities in both age and causes to other UK fans and debris cone outlined in Table 6.8.

Table 6.8: Ages of aggradation phases on British upland fans and debris cones, developed from Dunsford (1998)
[Minimum date refers to oldest datable horizon, though not necessarily the basal unit, hence deposition could be older (>)]

Region	Site Details	Author	Minimum		Reactivation	
			Age (^{14}C BP)	Cause	Age (^{14}C BP)	Cause
Scottish Highlands	Dalness Chasm, Glen Etive (NN 192 514)	Brazier *et al.* (1988)	> 4480 ± 300 (SRR-2284)	End of first aggregation, decline in paraglacial material	550 ± 50 (SRR-2882)	Human induced vegetation change
	Glen Feshie (NN 854 903)	Brazier and Ballantyne (1989)	>2020 ± 50 (SRR-2876)	-	320± 50 (SRR-2880)	Increased climatic wetness. High magnitude storms.
	Coire Dionachd, Glen Etive (NN 167 506)	Dunsford (1998)	>4, 485 ± 50 (SRR-6017)	Climate induced forest change to blanket peat	No datable evidence	Probable similar to Dalness reactivation
	Edendon Valley (NN 715 776)	Ballantyne and Whittington (1999)	2090 ± 40 (SRR-5946)	High magnitude event (s)	1. pre 1935 ± 45 (SRR-5945) 2. post 920 ± 40 (SRR-5942)	High magnitude event(s). Climatic and clearance discounted
Southern Uplands	Hopecarton Burn, River Tweed (NT 128 309)	Tipping and Halliday (1994)	950 ± 40 (SRR-4572a)	Not known	NONE	
	Dry Cleugh, Yarrow Water (NY 218 170)	Dunsford (1998)	3565 ± 45 (SRR- 6022)	Climatic optimum, marginal landuse	895 ± 45 (SRR 6019) 610 ± 40 (CAMS- 41323)	1.Post Viking settlement (grazing + woodland clearance) 2.Post climatic optimum and Monastic landuse
North Pennines	Harthope Beck, (NY 855 323)	Dunsford (1998)	19,235 ± 130 (AA-24207)	IMPOSSIBLE, as area glaciated, age due to carbon incorporation from limestone bedrock	None	

Table 6.8 cont:

Region	Site Details	Author	Minimum		Reactivation	
			Age (^{14}C BP)	Cause	Age (^{14}C BP)	Cause
Howgill Fells	Burnt Gill, Langdale (NY 662 016)	Harvey *et al* (1981)	940 ± 95 (UB-2213)	At time of Viking sheep introduction	None	
	Thickcombs Gill, Bowderdale Valley (NY 677 013)	Dunsford (1998)	None		1.930 ± 40 (AA-24205) 2. 790 ± 45 (SRR-6025)	1. Viking sheep farming, storm event 2. Monastic sheep farming
	Gully Fan, Bowderdale Valley (NY 674 021)	Dunsford (1998)	None		1. 300 ± 40 (SRR-6028) 2. 195 ± 40 (SRR 6027)	1.Onset of Little Ice Age 2. Cessation of Little Ice Age During LIA, colder temps., peat formation, and sheep grazing
Bowland Fells	Whittendale, River Dunsop (SD 653 561)	Harvey and Renwick (1987)	1200 ± 70 (WIS- 1627)	Post Viking sheep introduction	None	
	Castle Fan, Langden Valley (SD 604 503)	Harvey and Renwick (1987)	980 ± 70 (WIS- 1611)	Post Viking sheep introduction	None	
	Fiendsdale Fan, Langden Valley (SD 599 499)	Harvey and Renwick (1987)	1970 ± 70 (WIS- 1612)	Bronze/ Iron age settlement	None	
	Little Harden Fan, Langden valley (SD 623 508)	Harvey and Renwick (1987)	2000 ± 70 (WIS- 1615)	Bronze/ Iron age settlement	1020 ± 70 (WIS- 1616)	Post Viking sheep introduction
Lake District	Iron Crag, Caldbeck Fells (NY 305 344)	This study	>2035 ± 40 (SRR-6602)	-	Post 845 ± 55 (SRR- 6600)	Coincident with Monastic landuse and climatic deterioration
	Seathwaite Fan, Borrowdale (NY 235 111)	Boardman and Smith (1994); Parker *et al.* (1994)	No ^{14}C date, use pollen and local name	Deforestation with Vikings. 'thwaite' Scandinavian term for clearing.	None	

6.5 Conclusions

The foregoing analysis has considered the type of process activity, the timing and rates of activity, and potential causes of fan aggradation over historical time scales. Two timescales are considered, namely recent history (decadal) and longer-term (millennial).

Aerial photograph analysis of recent changes has revealed aggradation and vegetation recovery to occur in short periods of time. Processes responsible for aggradation since 1953 have included both fluvial and debris flow events, though the fluvial activity occurs more commonly. It is possible that activity since 1970 and particularly after 1995 with a channel incision represent a renewed phase of activity in the Iron Crag system.

Particle size analysis of fan sediments revealed the existence of fluvial and debris flow deposits, though fluvial units are more common in terms of horizon frequency and total depth. This is probably a reflection of fluvial deposits being spread over wider areas of the fan and thus being more likely to be sampled in pit exposures. Deposition of coarse minerogenic sediment is greater at the fan apex (Pit 1) and declines towards the fan toe (Pit 3). Horizons of equivalent depth are younger in Pit 2 than Pit 3, and therefore support the greater rate of aggradation higher up the fan surface.

The palaeo-environmental reconstructions show an active phase of deposition to have occurred between 1200 AD and 1400 AD, achieving mean annual rates of between 0.55 mm and 11.7 mm. Since 1420 AD mean annual rates of deposition have been much reduced (0.77 to 0.99 mm), but evidence of reworking suggests that these may be underestimations of the true rate. The cause of the active Middle Age phase is largely considered to be of anthropogenic origin but climatic (including changes in storm event frequency and magnitude) explanations cannot be discounted. These timings and causes are comparable to other UK fan and cone chronologies.

The division of the net fan depositional volume (79 m^3) for the sediment budget monitoring period by deposit area provides an estimate of the annual rate of deposition. This is performed using both the largest deposit area 1687.29 m^2 (10.12.99) and smallest area of 799.32 m^2 (30.3.99). The result is a range of annual deposition between 47 mm and 99 mm, respectively. These values indicate a very active rate of deposition, exceeding process activity in the Middle Ages. However, the longer-term process rates were obtained from compacted sediment that will have been subject to reworking, and generally speaking, as the period of observation increases averaging will tend to reduce the main aggradation rate. Therefore the 1998-1999 process rate is not directly comparable. However, the high rates calculated for the period of field study do support the aerial photograph analysis, that since 1995 Iron Crag has undergone widespread fan activity.

CHAPTER 7: CONTEMPORARY AND HISTORICAL FLOODING OF A FLUVIAL TORRENT, RAISE BECK

7.0 Scope of chapter

Raise Beck is a mountain torrent dominated by fluvial processes. Investigations of flooding at Raise Beck were undertaken following a recent event that blocked the A591 road and diverted the stream away from the Thirlmere catchment. These effects are both hazardous and costly. Raise Beck provides an interesting and unusual case study of a managed mountain torrent in the UK and raises some important general questions about flood estimation in steep mountain catchments.

Section 7.1 provides a context for upland flooding in the UK and more specifically the reported occurrences of flooding in the Lake District. The aims and objectives of this study are given in section 7.2. Section 7.3 describes the Raise Beck study site, and outlines a history of the Beck with regard to channel change. Section 7.4 outlines the field methods used for the collection of data on the 1995 and older floods, including geomorphological reconnaissance, channel geometry measurements, boulder measurements and lichenometry. It also considers analytical methods, specifically the palaeohydrological reconstruction of flow velocity and discharge. Results are given in section 7.5: this is divided into a number of sub-sections which examine the 1995 flood event, historical flood activity, the post-1995 flood engineering works, and finally a consideration of future flooding at the site in the context of the engineering modifications and anticipated climate change.

7.1 Background to UK and Lake District upland flooding

7.1.1 UK flooding

Reports of flooding and the impact of floods in the UK are numerous. McEwen and Werritty (1988) list some of the published studies for Scotland. Acreman (1989) notes 69 water courses throughout the UK which have been subject to extreme flooding in historical times. There are also several good examples of detailed case studies of the geomorphological impact of storms and upland floods: these include

Newson (1980), who investigated the effectiveness of two floods at Plynlimon; Carling (1986) in reference to the Noon Hill flash floods in the North Pennines; Harvey (1986) and Wells and Harvey (1987) in the Howgill Fells, Cumbria; and McEwen and Werritty (1988) who consider flash floods in the Cairngorms. Despite a growing body of literature on upland flooding, very few studies have investigated flooding in torrents. A notable exception is the investigation of the Allt Mor torrent by McEwen and Werritty (1988). Torrent systems deserve more attention both in the UK and abroad because they represent a significant resource in providing recharge to upland reservoirs.

7.1.2 Lake District floods

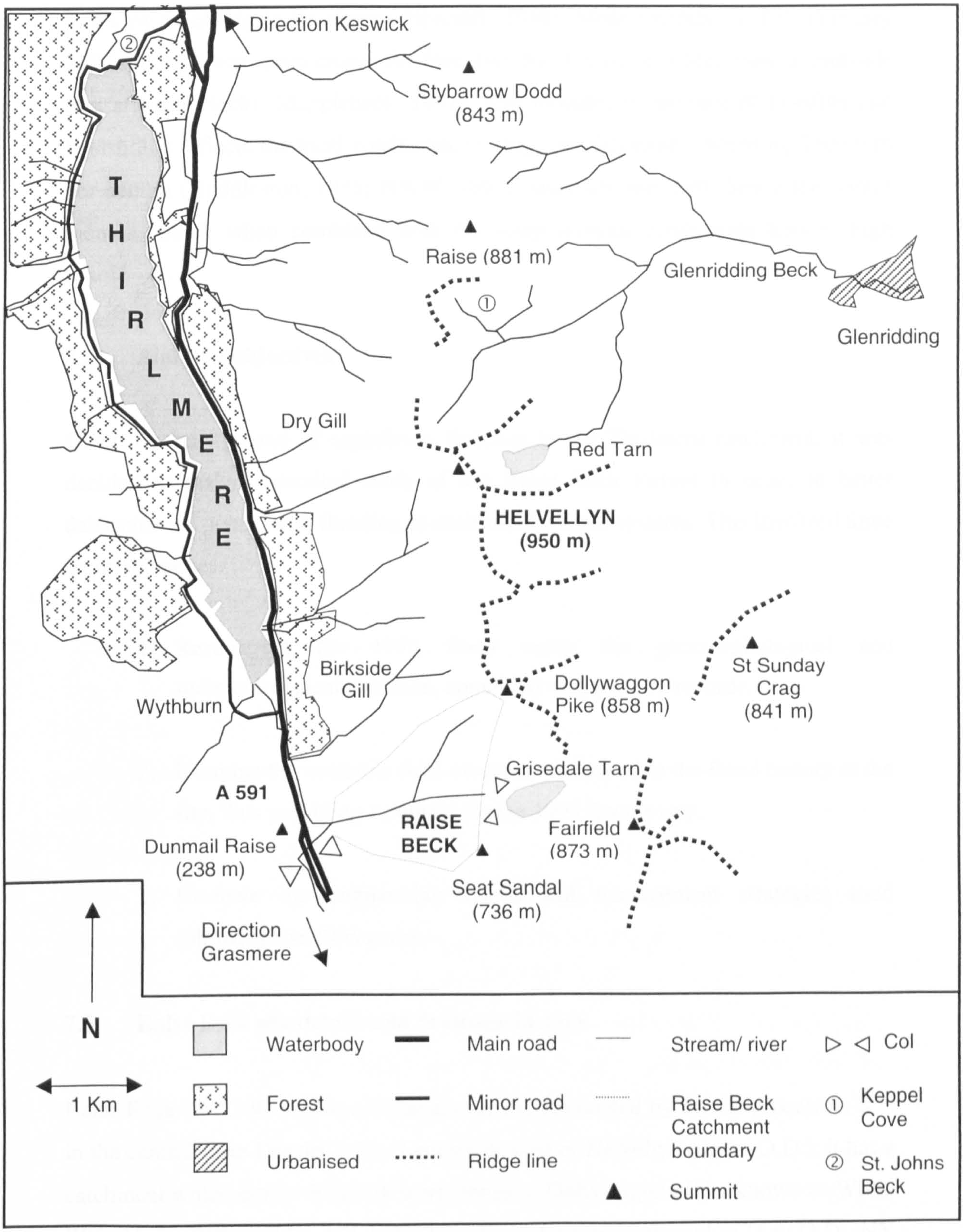
In common with many UK upland environments (McEwen and Werritty, 1988) the Lake District has a history of destructive upland and lowland flood events that have caused damage to infrastructure and property. However, detailed accounts of flooding in the Lake District are relatively few. Dodd (1996) describes the impact of a summer rainstorm on Lingmell Gill, a mountain stream to the west of Scafell Pike. A boulder deposit on the alluvial fan at the base of the stream (NY 182 072) is believed to relate to a flash flood generated by 175 mm of rainfall over a 36-hour period in August 1938. The impact of this flood appears to have been limited to the loss of pasture land. However, other documented floods have been more destructive. For example, Turner (1989) estimates that the Langdale and Borrowdale floods of 1966 cost an estimated £200,000 in loss of livestock, destruction of bridges, walls and roads, and damage to houses. The Westmorland Times (1966) stated *"The scene the next morning in Borrowdale was reminiscent of the Lynmouth Flood some years ago..."*

More substantial accounts and reconstructions of the impact of Lake District floods are provided by Warburton (1983), Carling and Glaister (1987), and Carling (1997). Warburton (1983) estimated the stream competence of a flood that occurred in Redacre Gill (Langdale) (NY 285 053) in January/ February 1967. This flood transported stream boulders, washed out the Blea Tarn road and flattened walls (Fishwick, 1983). Estimates of velocity and shear stress were calculated using palaeohydraulic equations which use boulder size as the independent variable, and other approaches not based on competence relations, i.e. Gauckler-Manning equation for velocity and Duboy's equation for shear stress. Values of velocity ranged between 3.1 m s^{-1} to 4.2 m s^{-1}, giving a maximum discharge of 72.7 m^3 s^{-1}. Shear stress values between 360 and 1000 N m^{-2} were reported. Carling and Glaister (1987) reconstructed the October 1927 dam burst of Keppel Cove (NY 345 164), which affected Glenridding Beck and the village of Glenridding (NY 387 169) (Figure 7.1). The breach released 14,000 m^3 of material from the moraine dam and 124,000 m^3 of water from the tarn behind. Dam break modelling produced a predicted discharge peak of 90-100 m^3 s^{-1}. The main impact of the flood was both degradation and accretion of the channel, the formation of four large boulder berms, and the destruction of property and loss of livestock. Carling and Glaister (1987) considered the maximum specific discharge of 10 m^3 s^{-1} km^{-2} in Glenridding village as not exceptional and might potentially be exceeded by a natural flood (e.g. the maximum probable flood discharge calculated from the Flood Studies Report [N.E.R.C, 1975]).

Carling (1997) outlined the effects of a storm occurring on the 23rd August 1749. It is reported that flooding of Mill Gill (NY 321 198) completely demolished Legburthwaite Mill and damaged surrounding properties. In the same storm Mosedale Beck to the north, on Threlkeld common (NY 355 240), also flooded affecting properties downstream and leaving fresh boulder flood deposits on the stream floodplain. Using these deposits, preliminary calculations of the flood hydraulics were produced. Critical shear stress values are in the range 80 to 200 N m^{-2}, velocities in the range of 3.3 to 4.3 m s^{-1}, and a specific discharge between 25 and 148 m^3 s^{-1} km^{-2}.

On the western side of the Helvellyn Massif at Thirlmere runs the A591, one of the main north-south roads in the Lake District. This has a history of flooding and landslides that have caused blockage of the road. A diary account of a storm on 2nd November 1898 (Kelbarrow, 1898) describes overbank deposits from Raise Beck on the road at Dunmail Raise and north towards Wythburn. The same account states the road was also blocked further to the north due to a landslip and flood deposits (see also Lakes Herald, 4th November 1898). Similar events have also occurred more recently, for example on 31st October 1977 thousands of tons of material were

Figure 7.1: The Raise Beck Study area



deposited by a new stream course (Westmorland Gazette, 1977). On 1st February 1995 Dry Gill (NY 323 152) and Raise Beck deposited material and water on the A591 road leading to its closure (Rycroft, 1998). Most recently on 17th February 1997 the road was again closed for four days by 40 tons of rubble from a landslide (not at Raise Beck) (Mapplebeck, 1997). This repeated occurrence of flooding and landsliding reflects the local conditions, i.e. high rainfall totals exceeding 2500 mm per annum (Huddleston, 1935; NWW, 1997), snowfall and melt during the winter months, which when combined with the steep igneous catchments lead to high runoff.

7.2 Aim and objectives

Given the background of significant flooding in the Thirlmere catchment, it was decided to make a detailed study of the Raise Beck torrent in order to better determine the controls on flooding in such small upland systems. This involved three main objectives:

1) Reconstruct the 1995 flood using the geomorphological and sedimentological evidence, combined with archive records.

2) Examine the available field evidence to determine the flood history at the site, thus providing a context for the 1995 flood event.

3) Evaluate the engineering works and management strategies used following the 1995 event.

7.3 Raise Beck site details and drainage history

Raise Beck (NY 330 118) is a mountain torrent dominated by fluvial processes. It is in the central Lake District Fells, 3 km south west of Helvellyn (950m O.D.). It has a catchment which drains the south west slopes of Dollywaggon Pike known as Willie Wife Moor (858 m O.D., NY 343 132), slopes leading to the col (574 m O.D., NY 343 121) near Grisedale Tarn, and north west of Seat Sandal (736 m O.D., NY 343 115). Raise Beck ranges in altitude from 790 m O.D. near the head of Dollywaggon

Pike to 235 m O.D. where it emerges at the pass of Dunmail Raise where the A591 trunk road crosses. (Figure 7.1). The catchment area of the Beck is 1.27 km^2 and the mean catchment slope is 0.206 m m^{-1} from the head at Grisedale col, and 0.235 m m^{-1} from the head of Dollywaggon Pike. The catchment has two main first order streams, one originating from Dollywaggon Pike (Reach 1) (Figure 7.2, Figure 7.3 A) and the other from Grisedale col (Reach 2) (Figure 7.2, Figure 7.3 A). These combine to provide the main second order channel at 500 m O.D. (Reach 3) (Figure 7.2, Figure 7.3 A/ B), which then receives several small tributary streams mainly from the left bank side. Below 450 m O.D. Raise Beck is a third order drainage stream. The first order channels are narrow, sinuous, step-pool streams with few large sediment sources. By contrast the second/ third order stream is much wider, has a steeper gradient ranging from step-pools to waterfalls, contains abundant sedimentary material (including multiple flood deposits), and has significant slope-channel coupling from screes and shallow streamside landslides. At the fan apex (300 m O.D.) the third order stream bifurcates, but most of the flow is artificially diverted down the right branch (Reach 4) (Figure 7.2, Figure 7.3 B/C). At this point the gradient reduces and the channel is less confined. The channel is still dominated by boulders and bedrock. The left bank channel at the fan apex is a continuation of Reach 3, which becomes Reach 5 after the road (Figure 7.2, Figure 7.3 B/C/D). Reach 5 is initially an unconstrained meandering channel with gravel bars and local bedrock outcrops. Variability in sediment size and channel capacity throughout the catchment is shown in Figure 7.4. This illustrates the small channel capacities and sediment sizes of Reaches 1 and 2, and the noticeable increase in the size of both in Reach 3 above the fan apex. Below the fan apex both channel capacity and sediment size start to decline, a trend that dramatically increases after the road (Reach 5).

The entire catchment is underlain by Ordovician Borrowdale Volcanic rocks (Moseley, 1978). These include dacitic lapilli tuff, andesite sills, tuff and volcaniclastic sandstone, and welded rhyodacitic lapilli tuff with breccia (BGS, 1999). Peat, grasses and reeds dominate the surface cover of the catchment above 500 m O.D. Below 500 m O.D. bedrock is more frequently exposed and thin soils, till deposits, scree, and larger boulders dominate the steeper slopes. Bracken cover becomes significant below the fan apex.

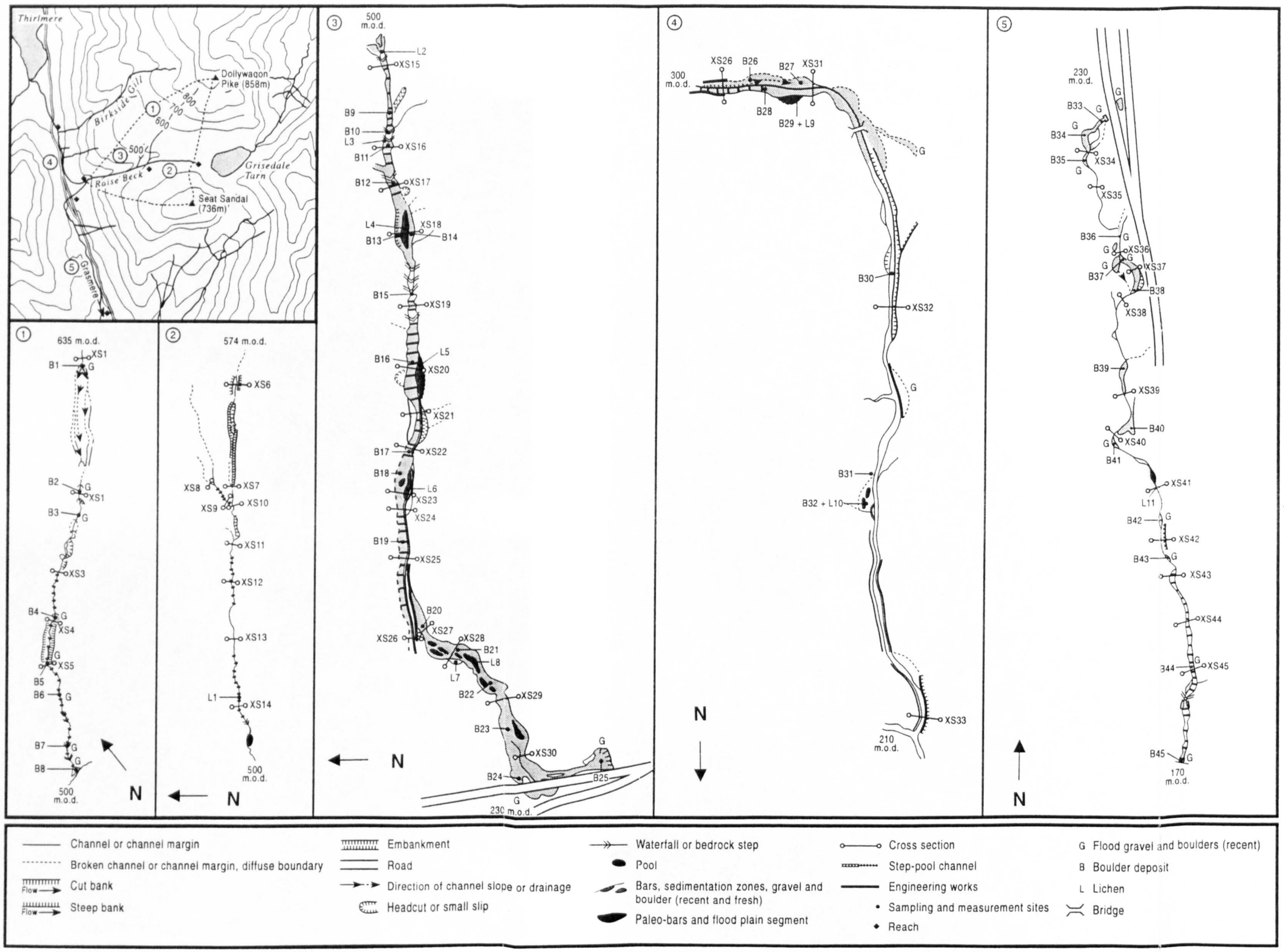


Figure 7.2: Raise Beck channel features and designated reaches

Figure 7.3: Oblique aerial photographs of the Raise Beck catchment (Taken 7.5.00)
(A- Reach 1 &2; B- Reach 3; C- Lower reach 3 and Reach 4; D- Reach 5)

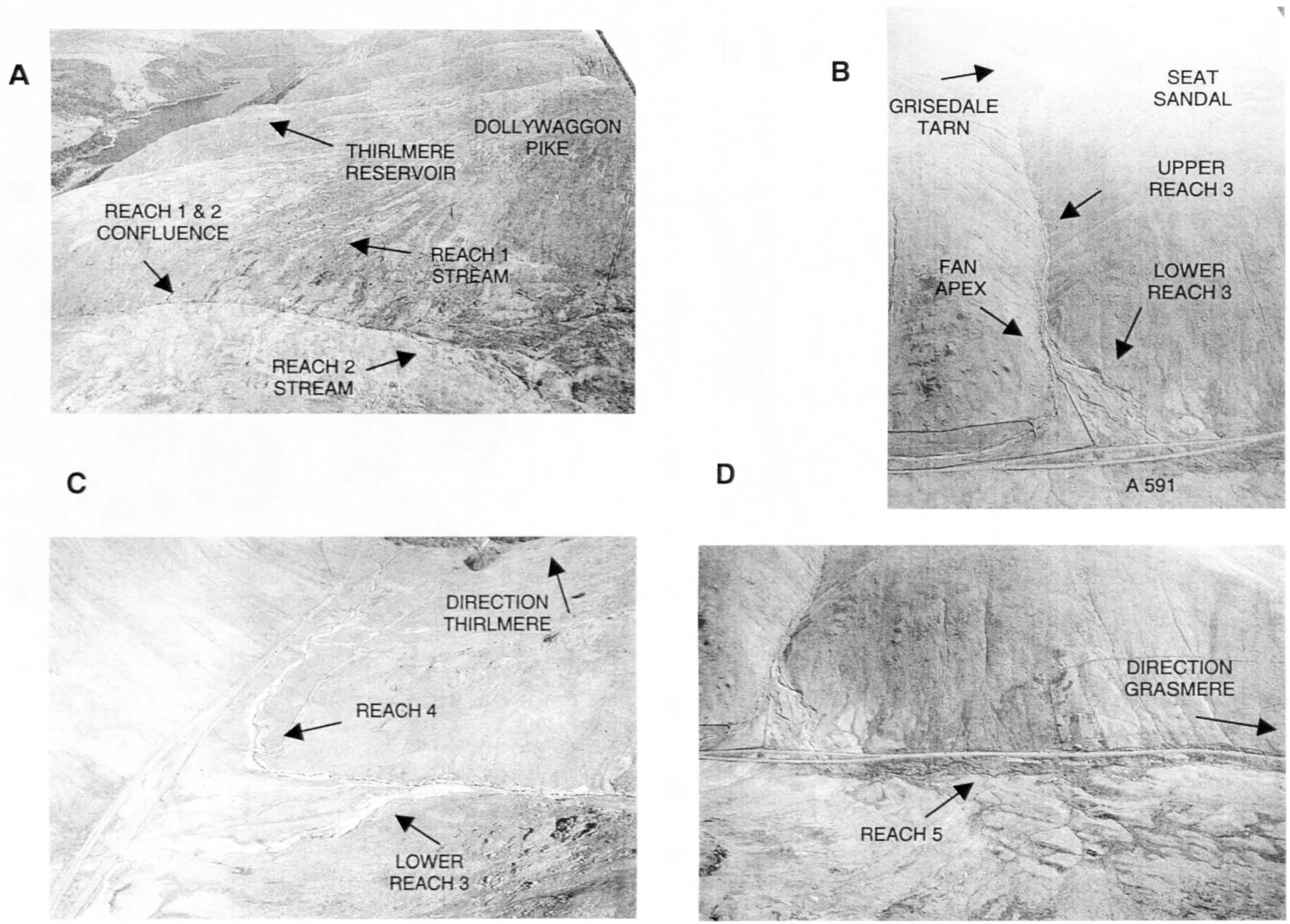
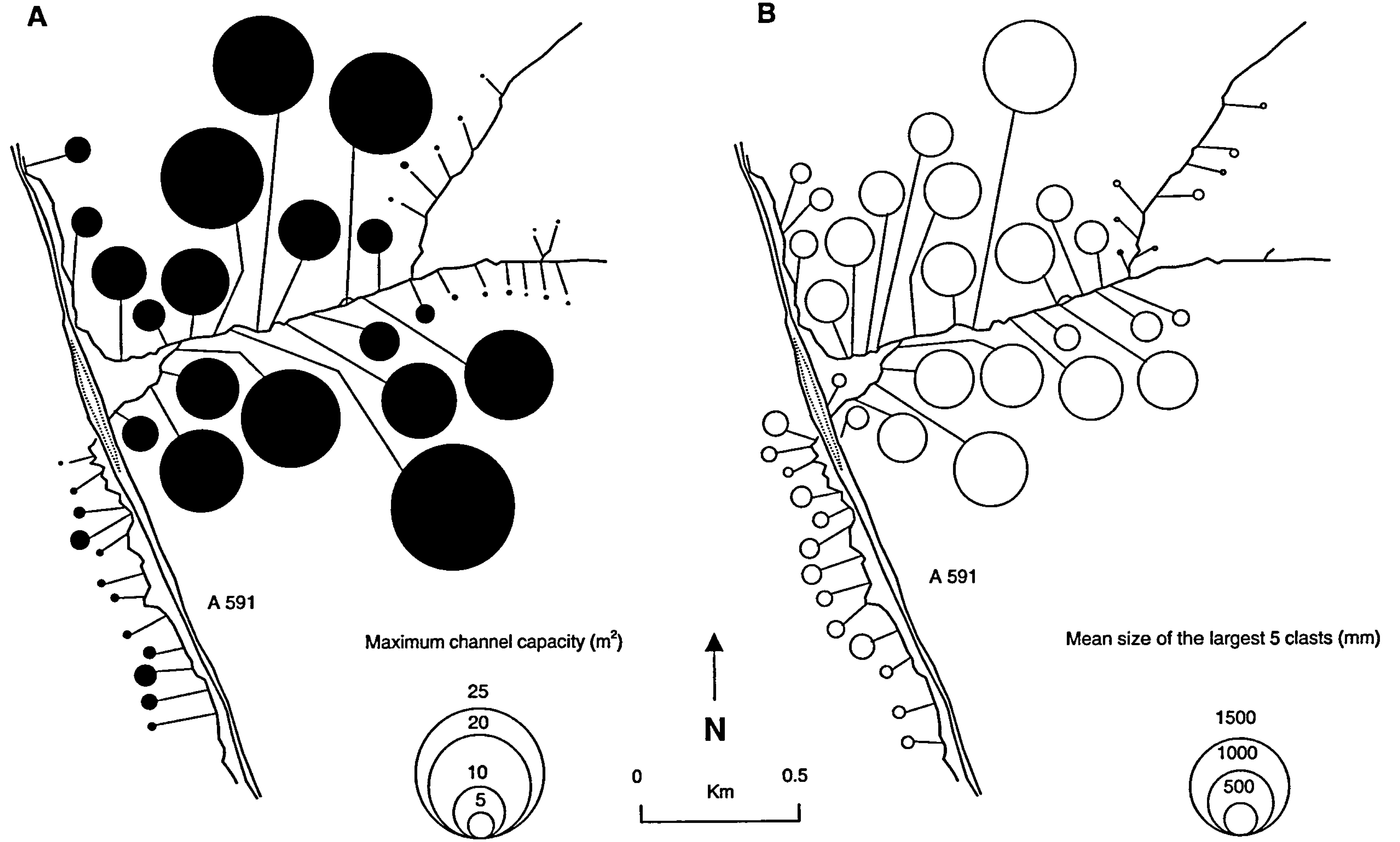


Figure 7.4: Spatial variability of maximum channel capacity (A) and the mean size of the largest 5 clasts (B) in the Raise Beck catchment.



Raise Beck forms part of the catchment area for Thirlmere reservoir, which was constructed between 1890 and 1894 and impounded by building a dam across a gorge in St John's Beck. This increased the size of two smaller lakes (Leathes Water and Wythburn Water) which existed prior to the engineering (Harwood, 1895; Hoyle and Sankey, 1994; NWW, 1997). The Manchester Corporation Water Works commissioned the scheme to supply the City of Manchester via an aqueduct from Thirlmere.

Raise Beck prior to the construction of the reservoir flowed southwards towards Grasmere, as indicated by Jefferys map of Westmorland in 1770 (Hindle, 1984) and the First Edition Ordnance Survey six-inch map (1860). The plans and sections for the reservoir and aqueduct submitted by Manchester Corporation Water Works show that Raise Beck was not captured for water supply in the initial scheme (Bateman, 1878), though the base of the fan would have been disturbed by the aqueduct construction. A transcript of a lecture given by J. Mansergh (10th April 1878) excludes Raise Beck as one of the streams to be captured by the scheme. It was therefore at some time after this that Raise Beck was diverted northwards to supply water to Thirlmere reservoir. An account by Kelbarrow (1898) indicates that in 1898 Raise Beck flowed north towards Wythburn:

"The road at the top of the Raise was so littered with stones...The Raise Beck from Helvellyn which goes under the bridge got out of its bed at the top of the field above. It came down in a flood through the meadows, buried the gate into the road with rubbish, and mostly went down to Wythburn, there is still a lot of water running that way..."

(Diary account, 5th November,1898)

But this was only temporary as the 1920 Edition Ordnance Survey map (Westmorland component survey revised in 1913) shows Raise Beck still flowing south into Westmorland.

Huddleston (January 1935, p29) states:

"The Raise beck ran into Grasmere until a few years ago, when a sudden flood breached into its right hand bank and since this occurrence the upper portion of this beck has delivered its water into Thirlmere."

The 1956 Ordnance Survey six-inch map (surveyed in 1951) confirms Raise Beck flowing northwards. Therefore the natural northward diversion of Raise Beck appears to have occurred a few years prior to 1935, but cartographic evidence can only fix this as sometime between 1913 and 1951. At some point the new channel course was stabilised with local engineering works.

Despite not knowing the exact timing of the diversion, Raise Beck has a history of geomorphologically significant floods as shown by in-channel boulder deposits and palaeo-channels in the basal fan. The most recent of these was the flood of 31st January 1995. This event caused the channel above Dunmail Raise to revert back to a southerly flow direction resulting in flooding downstream in Grasmere. The then National Rivers Authority (NRA) and local residents placed pressure on North West Water to once more divert Raise Beck northwards (Rycroft, 1998). Following these requests, in the spring of 1995 the lower reaches of Raise Beck were channelised using local material to create boulder-armoured defences (Rycroft, 1998). This contained the stream preventing flow divergence at the fan apex, which is the normal behaviour on an alluvial fan (Blair and MacPherson, 1994). This resulted in the majority of the flow being diverted north to Thirlmere. A small pipe was inserted into the bed of the north channel in May-June 1999 to allow a small compensation flow down the southerly course to Grasmere.

7.4 Field and analytical methods

7.4.1 Methods applied in the field

Initial field work involved a geomorphological reconnaissance of the site, to provide an overview of the catchment characteristics, i.e. fluvial features, hillslope features, and vegetation characteristics. This assessment highlights the existence of palaeoflood deposits, recent features belonging to the 1995 flood, and the engineering modifications undertaken after January 1995. Maps of the Beck (Figure 7.2) show flood deposits of multiple ages, the location of boulder deposits, the locations for channel cross-sections, tributary confluences, slope sediment sources, and engineering modifications to the channel.

Using aerial photographs (taken 25.7.95) as a base map, geomorphological and sedimentological evidence of floods was collected. Channel cross-section dimensions were measured to estimate channel capacities of flood and engineered channels. Boulder diameter measurements were taken to estimate the competence of the flood. Lichen diameter measurements were made to estimate the age of palaeo-flood deposits. Observations of channel slope were recorded at key points along the stream.

Channel cross sections are taken in accordance with the methods of Williams and Costa (1988); that is, close to features of interest, in this case boulder deposits and engineered sections; where water scour marks from the 1995 flood were evident; and at major changes in the channel. Measurements are made with a range of instruments according to the size and complexity of the section. In Reaches 1, 2 & 5 cross section form was measured using a levelled tape and rule. The larger cross sections in Reaches 3 and 4 were surveyed using a level and stadia pole, though one section required the use of a total station due to its depth and inaccessibility.

Boulder measurements: the intermediate axis (b axis) is measured on a minimum of 25 boulders in each deposit, specifically targeting the largest boulders amongst the deposit. Boulder deposits are initially defined by field mapping and confirmed by careful examination of stratigraphic and sedimentological arrangements, in order to discount boulders of a non-fluvial origin and to establish whether or not they were deposited by the 1995 flood event. Selecting the largest boulders is based upon the assumption that a mean of the largest particle sizes may reflect the maximum competence of the stream flow during flood (Costa, 1983; Williams, 1983; Williams and Costa, 1988; Clarke, 1996.)

Lichen measurements of *Rhizocarpon spp.* are made to the nearest millimetre, using a ruler. *Rhizocarpon spp.* are used as they are the dominant lichen on Raise Beck flood deposits, for which local lichen growth curves are also available (Lunan, 1969; Harvey *et al.*, 1984; and Macklin *et al.*, 1992). The field technique advocated by Innes (1985) is adopted, i.e. the longest axis (maximum diameter) of all shape lichens, being careful to eliminate coalesced thalli from the sample. The largest lichens in the deposit are recorded and the mean of the five largest thalli calculated. Lichenometry has been criticised by Worsley (1990) on the grounds that it is conceptually unsatisfactory both with respect to its basic assumptions and its method of field application. Despite these difficulties it has proved robust in dating flood deposits in the UK (Harvey *et al.*, 1984; Carling & Glaister, 1987; Macklin *et al.*, 1992; Merrett and Macklin, 1998, 1999). Harvey *et al.* (1984) showed that lichen-dated flood units corresponded with both aerial photographs and soil development. Macklin *et al.* (1992) validated their lichen curve by dating a number of control substrates of known age which resulted in good age agreement.

7.4.2 Methods of flood event reconstruction

Estimating the magnitude of rare hydrological events in upland catchments is difficult because such catchments are usually ungauged and detailed knowledge of catchment characteristics and runoff generation mechanisms are unknown. Therefore when a major flood occurs in a mountainous catchment flow characteristics need to be reconstructed from simple models using rudimentary catchment parameters (e.g. rational method, Flood Estimation Handbook), from geomorphological evidence (high water marks) or from sedimentological data (flow competence relationships for boulders). The Raise Beck flood of January 1995 was not gauged but can be estimated using all three types of method outlined above.

Williams (1988) defines palaeohydrology as the study of prehistoric waters, dealing with the characteristics of former rivers and their channels, though the techniques are also applicable to modern ungauged catchments. Maizels (1983) states all palaeoflow determinations are based on either hydraulic relationships between sediment and flow, or geomorphic relationships between channel morphology, channel sediments and discharge measurements. These approaches require an input of initial field data. The field measurements taken in this study (Figure 7.2) include: 45 Channel cross section profiles which allow the calculation of channel capacity, width of flow, depth of flow, hydraulic radius etc.; local channel bed slopes; and the intermediate axis of the largest boulders in 45 deposits, though not all of these relate to the 1995 event. The field data used to reconstruct the velocity and discharge of the 1995 flood are limited to measurements made in Reach 3, as it is only in this reach that boulder deposits and channel cross sections can be clearly attributed to the 1995 flood. Reach 5 contains a few boulder deposits relating to the 1995 event, but these are not used for velocity and discharge reconstruction, as the flood was diverted by the A591 before this reach. The exclusion of these data has no impact on the calculation of the peak flood conditions, as boulder deposits and channel sizes are smaller in Reach 5 than upstream in Reach 3.

Channel capacity calculations for an individual cross section vary according to the definition of the water surface, which is determined by different elevations of turf scour marks and sediment deposits on opposite channel banks. Usually, several possible peak stage heights can be defined. Further variability in reconstructing flood capacity is due to the inclusion or non-inclusion of fresh boulder deposits on the channel bed. Given these uncertainties it is possible to define a maximum and minimum channel capacity for each section.

As channel cross section measurements are very localised, two cross sections are used in the calculation of channel geometry variables (i.e. hydraulic radius, mean flow depth etc.). Similarly, in the discharge calculations, mean values of channel capacity are used, i.e. the mean of the maximum and minimum values from two cross sections. The cross sections selected include the cross section nearest to the deposit and the previous one upstream, as it is from an upstream location that boulders would have been entrained. Also, channel slope values are the mean of measurements between the two cross sections.

Hydraulic and geomorphic approaches are used to calculate velocity. In some hydraulic relationships particle size is used as the independent variable, following the assumption that the largest particles within a flood deposit are representative of the maximum competence of the stream during flood, if the deposit is of fluvial origin (Costa, 1983). The application of palaeo-competence equations to the reconstruction of velocity ideally requires assumptions about flow conditions to be met: i.e. steady, uniform flow; logarithmic velocity profiles and fully submerged particles with low relative roughness values (Costa, 1983; Maizels, 1983). Although it is unlikely that most of these conditions are satisfied in a mountain flood, several hydraulic equations worthy of consideration are:

$$V = 0.18\, d_i^{0.487} \qquad (7.1)\ \text{(Costa, 1983)}$$

$$V_b = 5.9 \sqrt{d_i} \qquad (7.2)\ \text{(USBR, 1973)}$$

$$V = 0.20\, d_i^{0.455} \qquad (7.3)\ \text{(Costa, 1983)}$$

$$V = 0.27\, d_i^{0.40} \qquad (7.4)\ \text{(Costa, 1983)}$$

$$V = 3.699\, D^{(0.478)} \qquad (7.5)\ \text{(Clarke, 1996)}$$

in which V is mean velocity in metres per second (for all equations); V_b is bed velocity in metres per second; d_i is the intermediate diameter (b axis) of a boulder in metres for equation (7.2), and millimetres for equations (7.1, 7.3 and 7.4). Equation (7.1) is an average of four mean velocities for 11 boulder sizes ranging between 50mm and 3200 mm. The four velocities were calculated using two theoretical relationships i.e. Helley's (1969) method which calculates balancing forces using turning moments, and secondly equating fluid drag (F_D) and lift (F_L) against gravitational frictional resistance (F_R) (Bradley & Mears, 1980). Also including two empirical methods, first a linear regression between observations of velocity and particle size compiled from a data set of published literature (Hooker, 1896; Grimm and Leupold, 1939; Lane, 1955; Wolman and Eiler, 1958; Fahnestock, 1963; Kellerhals, 1967; Ritter, 1967; Scott and Gravlee, 1968; Helley, 1969; Milhous, 1973; Glancy and Harmsen, 1975; Inbar and Schick, 1979; Shroba *et al.*, 1979; and, Thompson and Campbell, 1979). Secondly, data from the U.S. Bureau of Reclamation on riprap stability, where mean velocity is obtained by multiplying the bed velocity by 1.2, if the flow is turbulent and relative smoothness values (flow depth/ boulder diameter) are less than 2. The smoothness values for Raise Beck (Table 7.1) are both above and below this limiting value, the mean is 1.439. So a multiplier of 1.2 can justifiably be used. Equation (7.2, 7.3 and 7.4) are the empirical equations averaged in equation (7.1). Equations (7.3 and 7.4) are both from the data set compiled by Costa (1983). Equation (7.4) is a hybrid of equation (7.3), having a different coefficient and exponent, for use with particles coarser than 500 mm. The theoretical approaches are not applicable to Raise Beck as both require the measurement of all three particle diameters and were developed for situations which are not strictly comparable with torrents. Equation (7.5) proposes a very similar empirical palaeo-competence equation to equation (7.1). The independent variable used is D, defined as nominal particle diameter, which is the cube root of the product of the three orthogonal axes in metres. Therefore, like the theoretical approaches, unless all the axes of particles are known the equation cannot be used.

Alternatives to these hydraulic equations are geomorphological equations, which use the relationship between a number of dependent variables to calculate velocity. These regime flow equations include:

$$V= 11D^{0.67} S^{0.33} \qquad \text{(7.6) (Lacey, 1934)}$$

$$V= \frac{R^{0.67} S^{0.50}}{n} \qquad \text{(7.7) (Gauckler- Manning)}$$

$$V= 3.17 R^{0.33} S^{0.12} \qquad \text{(7.8) (Jarrett, 1992)}$$

In equation (7.6) D is the mean flow depth (i.e. cross-sectional flow area divided by flow width [A/W]) in metres, and S is water surface slope, for which channel bed slope is used. In equation (7.7) R is hydraulic radius (cross sectional flow area divided by wetted perimeter [A/P]), and n is a resistance coefficient. The Manning's n is calculated here using equation (7.9). Jarrett (1992) states this empirical equation was developed for estimating Manning's n in natural mountain streams with cobble or boulder bed material, where the flow is clear, and the channel and banks are stable with limited obstructions. Of these assumptions only the bed material size and the stability of the channel bed are likely at Raise Beck. The channel bed gradients at

Table 7.1: Mean velocity (m s^{-1}) calculations for the 1995 flood at Raise Beck based on boulders and cross sections, using a range of hydraulic and geomorphological equations. Boulder deposits B17- B20 & B23 do not have velocity values where the equation uses cross sectional information, as one or more of the associated cross sections is engineered following the 1995 flood.

Factor/ Deposit	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20	B21	B22	B23
Cross sections	15, 16	15, 16	15, 16	16, 17	17, 18r	17, 18l	18r, 19	19, 20	21, 22	22, 23	24, 25	25, 27	27, 28	28, 29	29, 30
Slope (m m^{-1})	0.3297	0.3297	0.3297	0.1793	0.2334	0.2334	0.3584	0.2334	-	-	-	-	0.2079	0.1879	-
Mean 5 largest boulders (mm) (b axis)	242	496	454	552	914	876	394	970	1418	810	848	960	886	1128	736
D_{84} (mm)	220	308	401.6	460	716	676	361.6	908	-	-	-	-	816	932	-
Average mean flow depth (D) (m)	0.6501	0.6501	0.6501	1.006	1.335	0.9975	0.8280	1.0835	-	-	-	-	0.7663	0.7720	-
Smoothness value	2.68	1.31	1.43	1.81	1.24	1.13	2.1	1.17	-	-	-	-	0.86	0.68	-
Mean Hydraulic radius (R) (m)	0.565	0.565	0.565	0.846	0.954	0.846	0.713	0.872	-	-	-	-	0.734	0.611	-
Mannings *n* (Jarrett, 1992)	0.230	0.230	0.230	0.171	0.186	0.189	0.229	0.188	-	-	-	-	0.185	0.183	-
Friction factor (*f*)	0.255	0.351	0.471	0.350	0.504	0.545	0.327	0.790	-	-	-	-	0.877	1.589	-
V (Costa, 1983)	2.607	3.698	3.542	3.896	4.980	4.878	3.306	5.127	6.168	4.696	4.802	5.101	4.905	5.518	4.482
V (USBR)	3.483	4.986	4.770	5.260	6.769	6.627	4.444	6.973	8.431	6.372	6.520	6.937	6.664	7.519	6.074
V (Data sets- All sizes)	2.430	3.369	3.236	3.537	4.449	4.364	3.034	4.571	5.433	4.211	4.300	4.549	4.386	4.896	4.031
V (Data sets- >500mm)	-	-	-	3.374	4.128	4.058	-	4.227	4.921	3.933	4.006	4.210	4.077	4.490	3.785
V (Lacey)	5.716	5.716	5.716	6.263	7.402	6.794	6.909	7.181	-	-	-	-	5.481	5.327	-
V (Gauckler-Manning)	1.702	1.702	1.702	2.213	2.524	2.284	2.087	2.342	-	-	-	-	2.001	1.699	-
V (Jarrett)	1.726	1.726	1.726	2.245	2.560	2.317	2.117	2.376	-	-	-	-	2.030	1.723	-
V (Darcy-Weisbach)	7.566	6.449	5.568	5.827	5.890	5.333	7.834	4.495	-	-	-	-	3.695	2.381	-

Raise Beck (0.179 to 0.358 m m^{-1}) are far greater than the friction slope range covered by the equation (0.002 to 0.052 m m^{-1}). The calculated *n* values for Raise Beck (0.171 to 0.228) are high compared to the normal values of mountain streams i.e. 0.05 to 0.07, though not unique, as Williams (1988) states that values as high as 0.4 have been reported. Bathurst (1978) considers *n* to range between 0.04 and 0.2 for natural coarse bedload channels. Also Carling & Glaister (1987) calculated *n* values using equation (7.9) between 0.087 and 0.149 for Glenridding Beck, a mountain stream approximately 5 km north-east of Raise Beck (see Figure 7.1), which has channel gradients as high as 0.236 m m^{-1}.

$$n = 0.32\, S^{0.38}\, R^{-0.16} \qquad \text{(7.9) (Jarrett, 1992)}$$

$$V = (8gRS/f)^{0.50} \qquad \text{(7.10) (Darcy -Weisbach)}$$

$$f = (1/\,(1.16 + 2\log(R/\,D_{84}))^{2} \qquad (7.11)$$

This difficulty of obtaining a friction factor is also the case with the Darcy-Weisbach equation (7.10), where g is gravitational acceleration (9.80665 m s^{-1}), and f is the friction factor. This can be estimated using Limerinos' (1970) relationship based on the D_{84} value (equation 7.11). Jarrett (1992), accepting the limitation of having to find friction factors, proposes equation (7.8) as an alternative for mountain rivers based on data from the Colorado data set (Jarrett, 1984). Like equation (7.9) it is intended for slopes of lesser gradient than Raise Beck.

Table 7.1 outlines some of the variables used in the previous equations and the resulting range of mean velocities, where boulder size is the mean of the largest five boulders, and those calculations involving channel geometry values are limited to boulder deposits associated with cross sections that have not been engineered following the 1995 flood. Engineered cross sections are excluded, as calculated channel geometry values would be different to those existing at the time of the flood at these locations.

To calculate discharge the continuity equation is used (equation 7.12), following Costa (1983), Maizels (1983), Williams (1983), and Clarke (1996).

$$Q = AV \tag{7.12}$$

It is first necessary to decide which velocity value is to be used. Equations (7.10 and 7.7) are rejected as they both involve a flow resistance variable, which is difficult to determine with accuracy. Equations (7.2-7.4) are not used, as they are components of equation (7.1). Equation (7.6), whilst simple, is rejected as some of the empirical data were obtained from canals with very low gradients (Williams, 1988). This leaves equations (7.1 and 7.8); both are specific to steep channels with boulders, but are still based on observations of stream systems with lower slopes than Raise Beck. Clarke (1996) states that high bed slope angles increase fluid turbulence and therefore flow resistance. Thus, the critical velocity required to initiate motion is less, thereby reducing the average velocity of the competent flow. Despite this, equations (7.1 and 7.8) remain the best available to estimate the mean flow velocity of the Raise Beck flood.

7.5 Results and discussion

7.5.1 Rainfall

Within the Thirlmere catchment ten rain gauges were once operational (Rycroft, 2000), the locations and altitude of these relative to Raise Beck are shown in Figure 7.5. North West Water reports (Rycroft,1999) that only 7 of these gauges were in use at the time of the 1995 event (labelled on Figure 7.5 as gauges 1, 3, 4, 6, 8, 9 and 10) and with the termination of the Wythburn gauge in December 1996, only six gauges remain operational (Metform, 1996). Table 7.2 shows the variability in monthly rainfall in the catchment immediately prior to January 1995, the total accumulation for January 1995, totals during the January 1995 storm, and gauge location relative to the Raise Beck fan apex. December 1994 is shown to be a wet month; indeed Sanders (1995) states that December rainfall at the Nook gauge was 184% of the long-term average (1941-1970, itself a period of higher rainfall in the UK: Rumsby & Macklin, 1994; Robson *et al.,* 1998). Sanders (1995) also states that between the 1st and 29th January at Dale Head Hall a total of 325.6 mm of rain fell, which was 141 % of that expected for 29 days in January. This above average level of

Figure 7.5: Rain gauges in the Thirlmere catchment. (Derived from Atkinson, ?, Pre 1970)

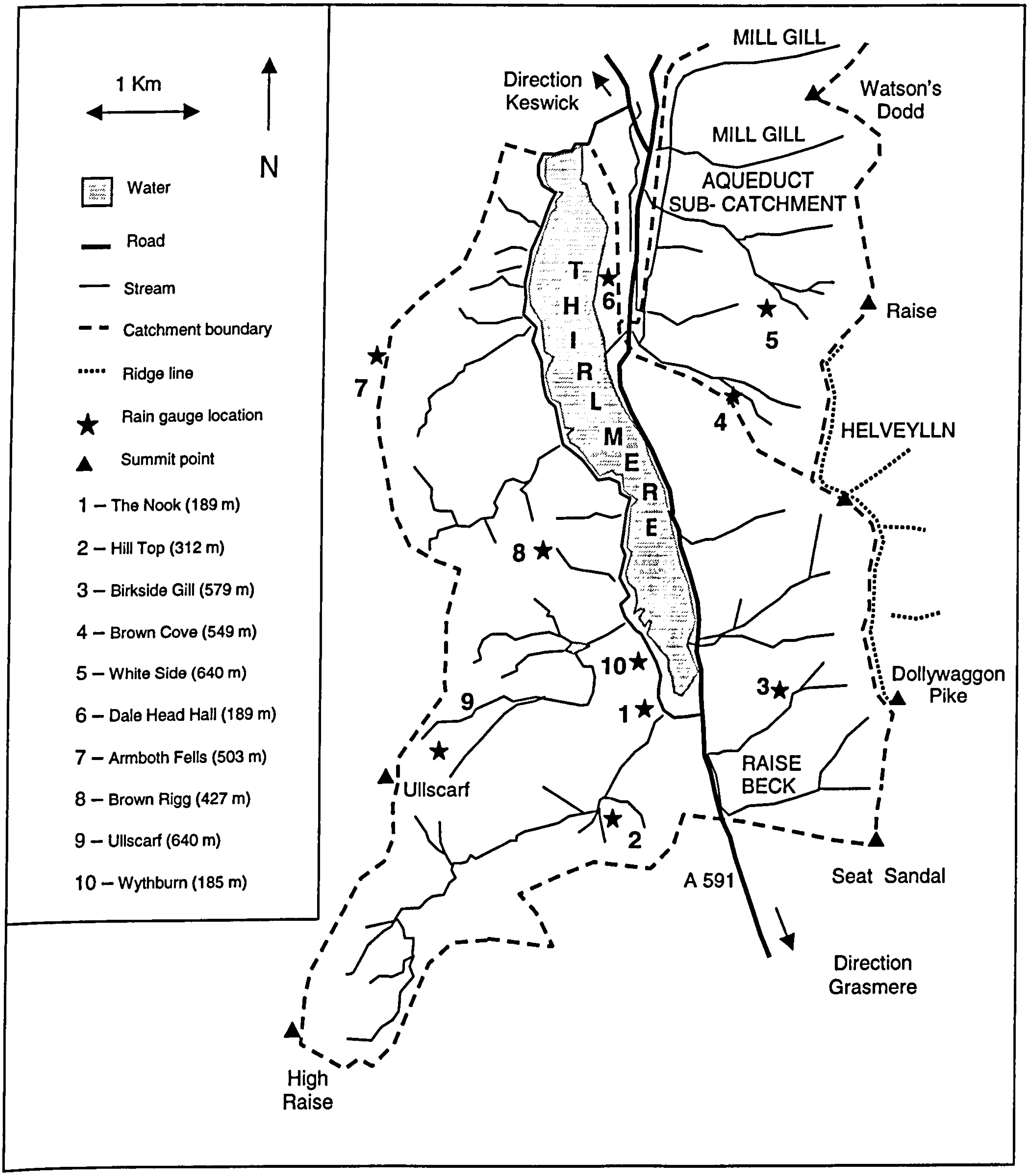


Table 7.2: Rainfall totals for rain gauges in the Thirlmere catchment: December 1994; whole January 1995; and January 1995 storm (Data sources: North West Water Rain gauge summary; North West Water monthly log; Environment Agency, North West Region-edited data). Supplemented with basic information about the rain gauges (altitude of rain gauge; and the approximate distance of the rain gauge from the Raise Beck fan apex).

Rain gauge	December 1994 total (mm)	January 1995 total (mm)	January 1995 storm total (mm)	Gauge Altitude (m O.D.)	Gauge distance from fan apex (km)
Birkside	500	900	-	579	1.26
Ullscarf	710	850	-	640	3.17
Wythburn	470	-	-	185	1.71
Brown Rigg	630	780	-	427	2.85
Brown Cove	480	550	-	549	4.25
Dalehead Hall	442	-	133.5	189	5.64
The Nook	540	555.4	163.5	189	0.95

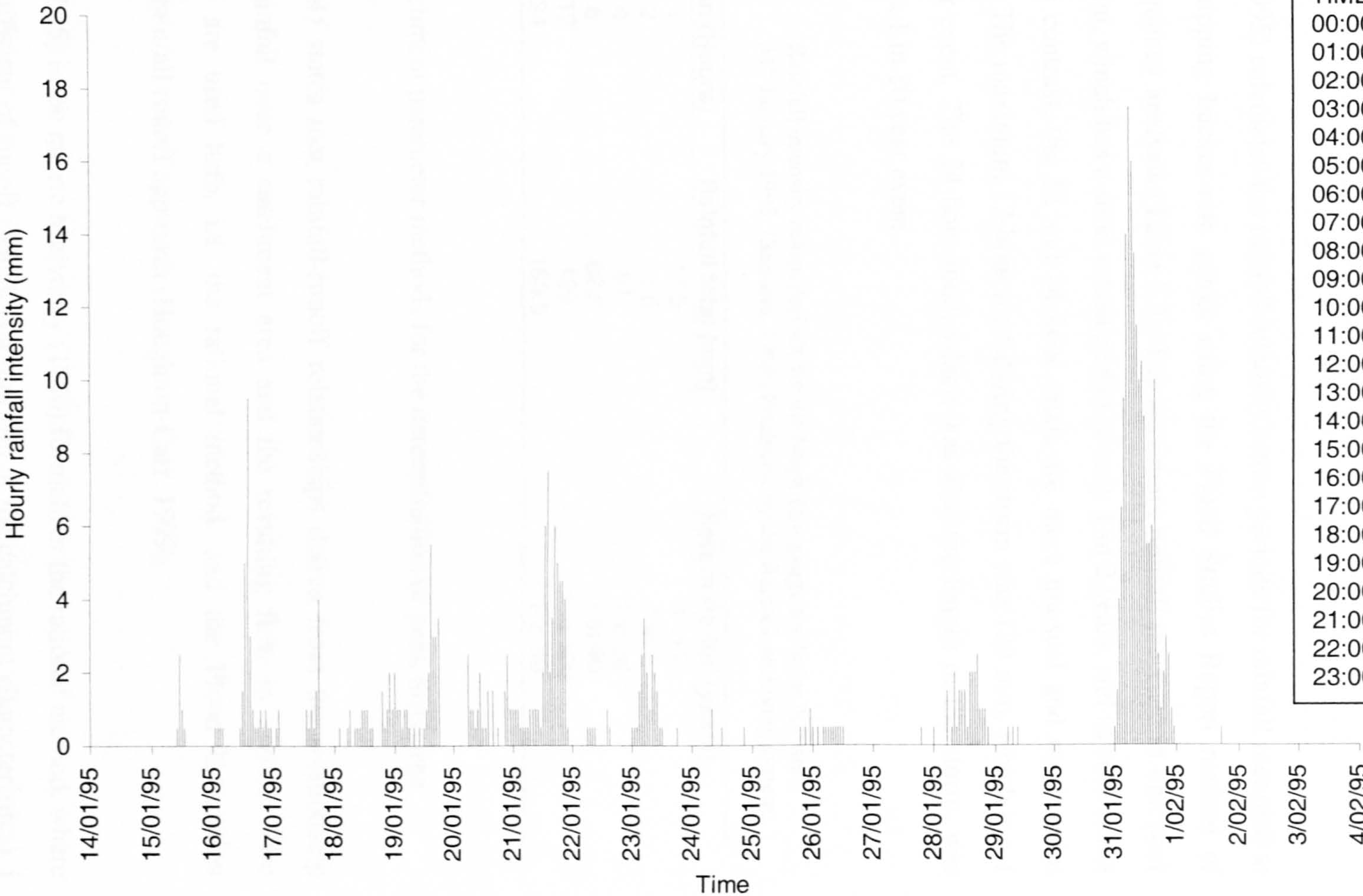
antecedent rainfall meant that the Thirlmere catchment was saturated prior to the intense rainfall on the rain days 30th and 31st January 1995 (rain day 0900 GMT + 24 hours). No soil moisture observations are available, though it is possible to calculate a surrogate catchment wetness index using antecedent rainfall totals (CWI) (Equation 7.13 & 7.14) (see Wilson, 1990; Houghton-Carr, 1999). In equation (7.13) SMD is the amount of water required to restore the soil to field capacity (which is taken to be 0 in winter), API5 is the rainfall total for the five days prior to the event, and the 125 value is to keep the CWI positive. In equation (7.14) P denotes the daily rainfall and the suffix indicates the numbers of days prior to the event. This calculation is a component of the FEH discharge calculation (section 7.5.2), and is 132.92 mm at 0900 on the 30.1.95 and 130.28 mm at 23.00 on the 30.1.95, i.e. the starting point of the storm. From the relationship of average annual rainfall to CWI (Wilson, 1990), the significance of these values can be determined. Given the average annual rainfall of 2528 mm at Nook (Environment Agency, 2000), the saturation of the ground is achieved at a CWI value of 128 mm. These values of soil wetness prior to the storm, with unquantified effects of initially frozen ground and snow, result in high a percentage runoff value. A large proportion of the falling rainfall was therefore effective, i.e. contributing to the rapid runoff.

$$CWI = 125 + API5 - SMD \qquad (7.13)$$

$$API5 = 0.5^{0.5}[P_{d-1} + 0.5\, P_{d-2} + (0.5)^2\, P_{d-3} + (0.5)^3\, Pd_{-4} + (0.5)^4\, P_{d-5}] \qquad (7.14)$$

The storm that produced the flood occurred between 2300 hours on 30th January and 2300 hours on 31st January. It was caused by a near-stationary front over the North Pennines and Cumbrian Mountains (Sanders, 1995). The Meteorological Office/ London Weather Centre summaries for the 30th and 31st January 1995 (Meteorological Office, 1995b) indicate that a depression crossing the UK was responsible, giving heavy rain to the north and west of the UK throughout the 31st January. Table 7.2 shows Dale Head Hall received a total of 133.5 mm and the Nook 163.5 mm (Figure 7.6), which are 54 % and 59 % of January long-term totals respectively. Snowmelt contributed to runoff during the storm. The Lake District National Park Authority records snowline altitudes and approximate snow depths on Helvellyn, but unfortunately records are only retained for one year.

Figure 7.6: Hourly rainfall data for the second half of January 1995 at the Nook (Gauge 592765, G.R. NY 319 129) (Data Source: North West Water Ltd / Environment Agency, North West Region)



Hourly rainfall data of 31st January 1995 event:

TIME	RAINFALL (mm)
00:00	0.5
01:00	1.5
02:00	4
03:00	6.5
04:00	9.5
05:00	14
06:00	17.5
07:00	16
08:00	13.5
09:00	11.5
10:00	10
11:00	10.5
12:00	9
13:00	5.5
14:00	5.5
15:00	6
16:00	10
17:00	2.5
18:00	1
19:00	2
20:00	3
21:00	2.5
22:00	1
23:00	0.5

The Blencathra Centre weather records (Meteorological Office, 1995a) indicate the presence of snow at elevations higher than the Blencathra Centre (NY 304 256, 270 m O.D., about 14 km to the north of Raise Beck) at 0900 on the 30^{th} January, but provide no specific detail of snow altitude, depth and when melting of snow pack began.

Sanders (1995) calculates the rainfall intensity return periods for rainfall recorded at the Nook tipping bucket rain gauge using the Flood Studies Report method of rainfall frequency analysis (Table 7.3). The maximum rainfall recorded in one hour was 17.5 mm, which has a short return period of only 1 in 2 years, and as such is not unusual. In contrast, the 12 and 24 hour totals are more unusual and much more significant. The maximum 12-hour total during the storm was 129 mm, which is a 1 in 100 year event. The 24-hour total, which was also the length of the storm, was 163.5 mm, a 1 in 80 year event.

Table 7.3: Rainfall intensity return periods for the Nook rain gauge totals for 30^{th} and 31^{st} January 1995. (Sanders, 1995) Produced by the Rainark archiving system.

Duration (Hours)	Rainfall total (mm)	Return Period (years)
1	17.5	1 in 2
2	33.5	1 in 6
4	61	1 in 20
6	82.5	1 in 40
12	129	1 in 100
24	163.5	1 in 80

7.5.2 Catchment parameter methods for the determination of peak discharge

Shaw (1994) states that rainfall-runoff relationships derive from the relationship between rainfall over a catchment area and the resulting flow in a river. Two approaches are used here, i.e. the rational method, and the Flood Estimation Handbook rainfall runoff approach (Houghton-Carr, 1999).

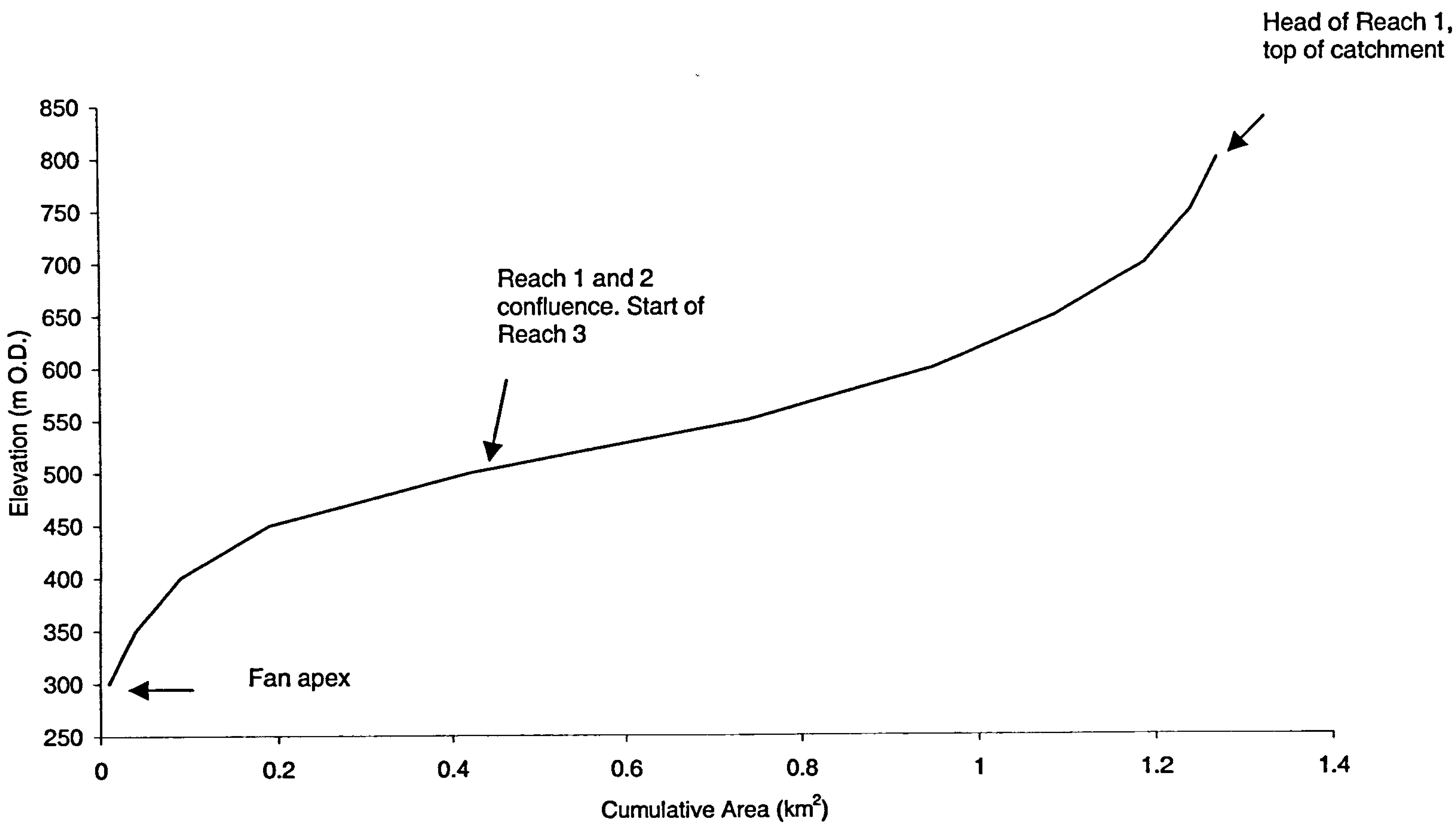
Equation (7.15) is the metric Mulvaney (1850) formula or the rational method, where C is the coefficient of runoff (which is a function of the catchment characteristics), i is the intensity of rainfall (mm h^{-1}) in time T_c, and A is the area of the catchment (km^2). T_c is the time to concentration, calculated using equation (7.16). Time to concentration is the time needed for rain falling at the perimeter of the catchment to reach the exit of the catchment, that is, the point at which Q_p (peak discharge- $m^3 s^{-1}$) is calculated. After the T_c period all the catchment is contributing to the flow.

$$Q_p = 0.278 \text{ CiA} \tag{7.15}$$

$$T_c = 0.00025 \left(L/ S^{0.50}\right)^{0.8} \tag{7.16}$$

In equation (7.16) L is length of the catchment along the longest channel (m) and S is the catchment slope ($m\ m^{-1}$). At Raise Beck L is 1830 m and S is 0.235 $m\ m^{-1}$. This gives a rapid time to concentration of 11 minutes. This rapid runoff contribution, along with the catchment characteristics and the catchment conditions prior to the storm suggests that a high coefficient of runoff should be applied to equation (7.15). The presence of peat in the catchment indicates that the rainfall runoff response will be flashy (Conway and Millar, 1960; Labadz, 1988; Burt *et al.*, 1990, 1997, 1998, 2000). The proportion of the catchment dominated by peat is that above 500 m O.D., which is 1.08 km^2 or 85 % of the entire catchment, as illustrated by Figure 7.7. Daily weather observations from the Blencathra Centre (Meteorological Office, 1995a) indicate that the week prior to the 30th- 31st January event had been cold with maximum temperatures up to 9 °C and minimum temperatures as low as -4 °C, and also wintry, with snowfalls occurring. Significantly the night of 29-30th January 1995 was frosty and as already stated the hilltops were snow- capped at 0900. Therefore it is likely that at higher elevations in the Raise Beck catchment the ground was to some extent frozen and snow-covered when the storm began (23:00, 30.1.95). Melt during the 30th January would have been low given it was a cold (< 4° C), dry day (Meteorological Office, 1995b). Under such conditions, Ward (1975) states that overland flow would be aided by the frozen ground surface, which prevents infiltration. Wade and Kirkbride (1998) also suggest such a 'concretic' condition leads to overland flow being established very quickly. However, the role of snow in runoff generation is complicated, as a frozen snowpack would delay runoff, absorbing rainfall and retarding the runoff until the snowpack was fully ripe and therefore unable to retain any more meltwater (Dingman, 1994).

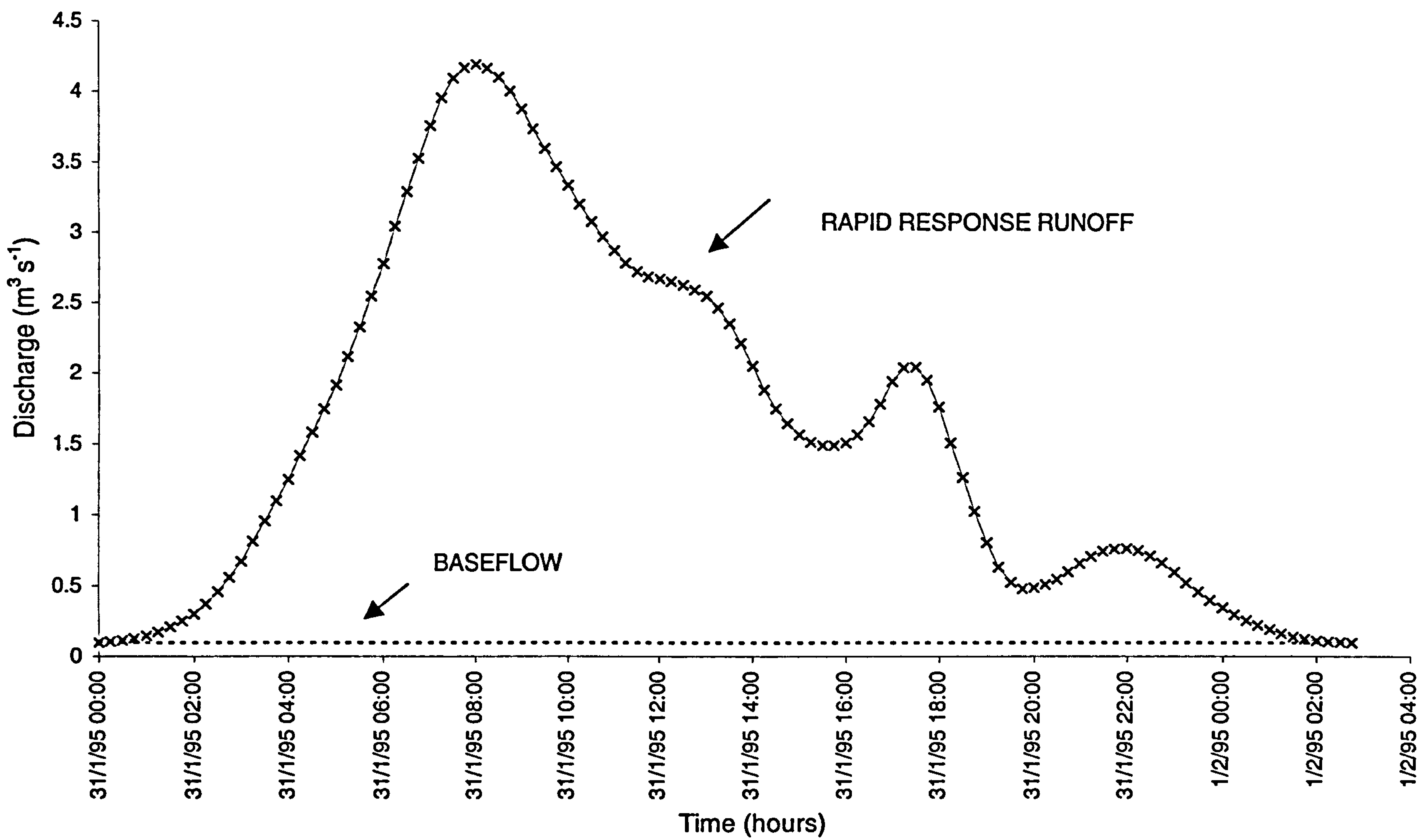
Figure 7.7: Raise Beck catchment hypsometric curve



The values for Raise Beck used in equation (7.15) are: C of 0.9 (slightly less than 0.95 as applied to impervious urban surfaces, Shaw, 1994). The maximum hourly intensity recorded in the storm was 17.5 mm h^{-1}. This is for a period longer than the T_c but the one hour value is the shortest time interval for which intensity values are available. The catchment area is 1.27 km^2. This produces a peak discharge value of 5.56 $m^3 s^{-1}$ at the fan apex.

Discharge can also be calculated using the Flood Studies Report rainfall-runoff approach, as restated by the Flood Estimation Handbook (FEH) (Houghton-Carr, 1999). In summary, this approach uses rainfall data for the storm (storm profile, storm duration and storm depth), and prior to the storm event, as the main inputs. This allows the calculation of a catchment wetness index (see section 7.5.1), percentage runoff, baseflow, the rainfall hyetograph, and the net rainfall hyetograph. The combination of the net rainfall hyetograph and a unit hydrograph allow the rapid response runoff hydrograph to be derived, which when combined with the baseflow gives the total runoff hydrograph. For a full explanation of this rainfall-runoff method see Houghton- Carr (1999). Using this approach the maximum reconstructed discharge at Raise Beck is 4.197 $m^3 s^{-1}$. The derived total runoff hydrograph (Figure 7.8), shows reconstructed discharge at 15 minute intervals from the start of the storm until the flow subsided to the baseflow level. A 15-minute interval was required as the time to peak (Tp) of the triangular unit hydrograph was 1.03 hours, and it is advised that ordinates of the unit hydrograph (U_t) should be well defined with a data interval of 10-20 % of the value of Tp (Hougton-Carr, 1999). As 20% is 12 minutes 10 seconds, a fifteen-minute interval is fairly appropriate. This meant assuming that each quarterly hourly rainfall total was exactly a quarter of the hourly fall. Further inaccuracies in the calculation of the discharge value occurred when using catchment descriptor regression equations in the absence of specific data. For example, Tp was calculated using a multiple regression equation which performs better on catchments larger than 100 km^2 (Houghton-Carr, 1999).

Figure 7.8: Derived total runoff hydrograph for Raise Beck at the fan apex, between 31.1.95-1.2.95., using the Flood Estimation Handbook (1999) rainfall runoff method



7.5.3 Palaeohydrological determination of flow characteristics

Figure 7.9 shows the downstream change in velocity at Raise Beck during the 1995 flood calculated using equations 7.1 and 7.8 (see Figure 7.2 for location of deposits). Both sets of velocity reconstructions show the same general behaviour, i.e. increasing velocity with distance downstream until boulder deposits 16/17. Thereafter velocity is nearly stable, with a decline starting at boulder deposit 21 which is just beneath the fan apex. The decline in velocity after the fan apex reflects the increase in available channel capacity due to the diverging flow in the 1995 event, and reduced valley confinement.

Discharge is calculated using the velocity values provided by equations (7.1 & 7.8), and mean maximum and mean minimum channel capacities reconstructed from the channel cross section measurements. The data used in the calculation of the discharge values and the resulting discharges are shown in Table 7.4 and Figure 7.10. The underlying trend is an increasing discharge in Reach 3 until the upper part of the fan. A decline in discharge in the lowest part of Reach 3 is only evident in values calculated using equation (7.8). The variability of discharge values is a function of the equation used to calculate the velocity and the range of reconstructed channel capacities relating to the 1995 event.

The variability in discharge resulting from the different equations used to calculate velocity is between 33.79 % and 68.76 % for each boulder deposit, with a mean difference of 49.89 % for all data (the percentage values indicate the extent to which discharge values using equation (7.8) are smaller than those using equation (7.1)). The difference in discharge as a result of the mean maximum and mean minimum channel capacities is between 12.09 % and 49.50 % for each boulder deposit, with a mean difference of 24.63 % (the percentage values indicate the extent to which discharge values using minimum channel capacities are smaller than those calculated using the maximum channel capacity). The largest instantaneous peak discharge of the 1995 event varies according to which velocity equation is selected. Equation (7.8) shows a peak in discharge values at boulder deposit 13. Whilst equation (7.1) provides a peak for boulder deposit 22, although similarly high values also occur at boulder deposit 13. Taking boulder deposit 13 as the deposit of

Figure 7.9: Raise Beck 1995 flood velocities using equation (1) Costa (1983) and (8) Jarrett (1992)
(Deposits 17-20, 23 and 24-25 are either engineered or non- channelised so equation 8 is not applicable)

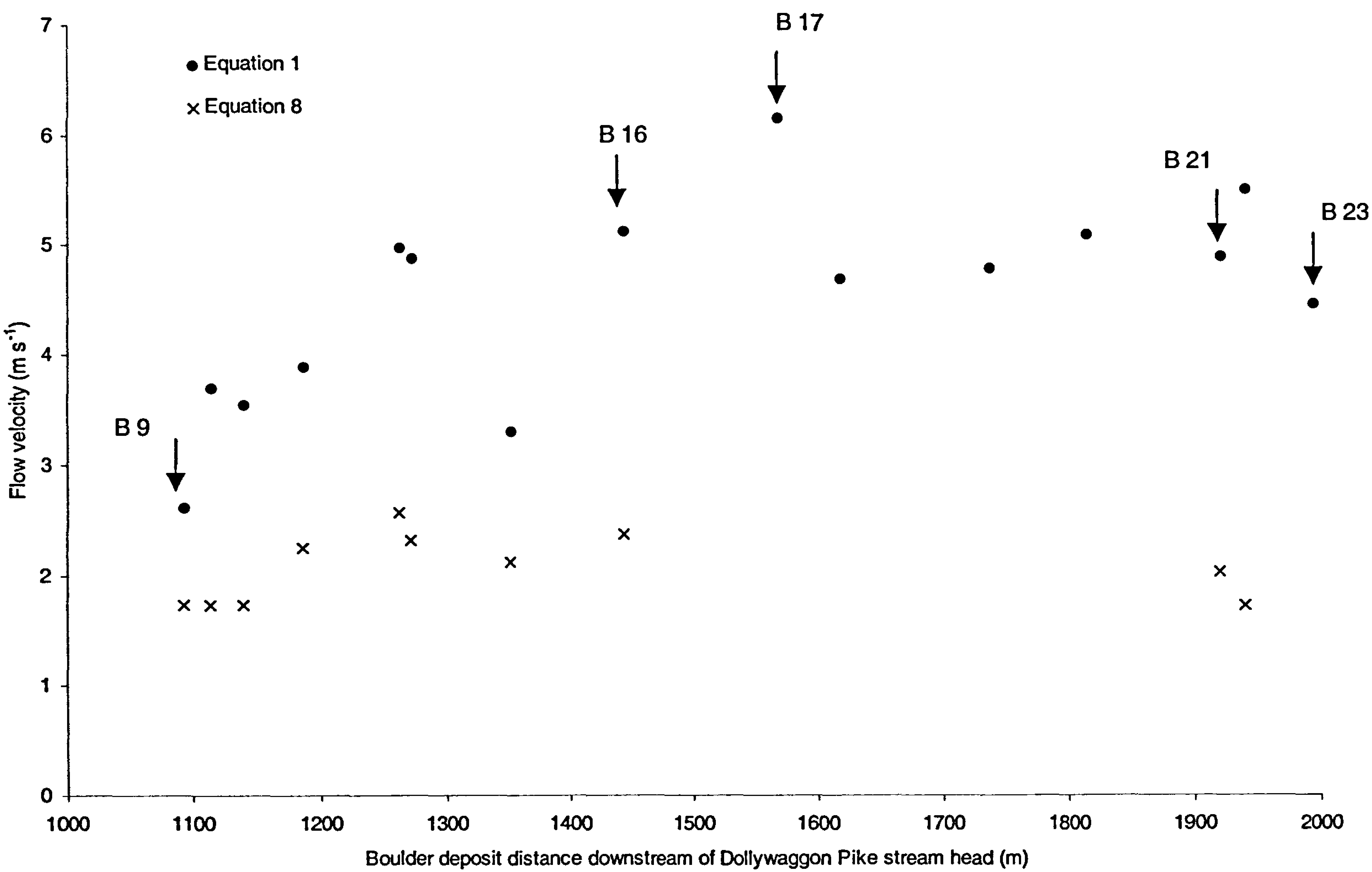
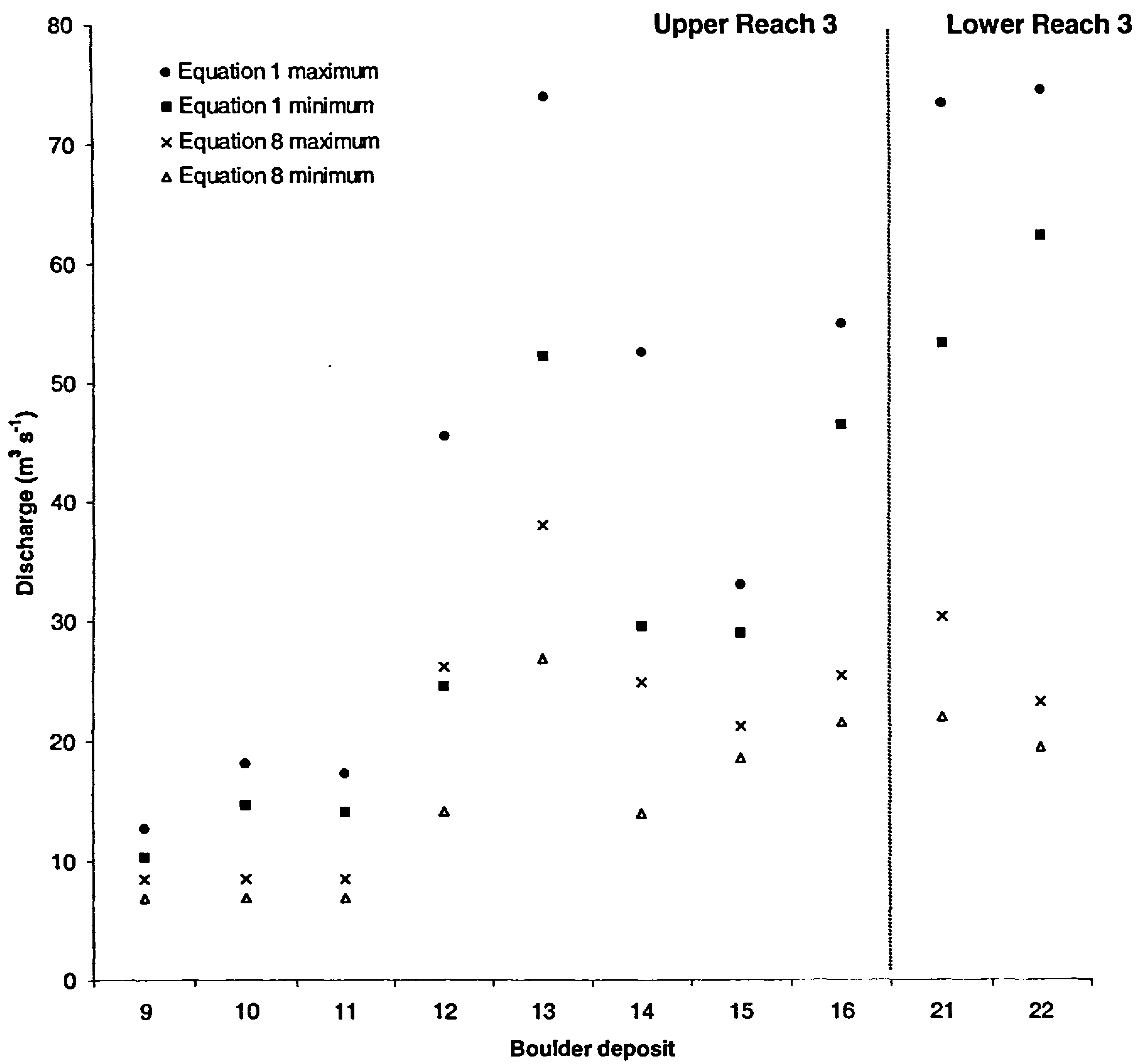


Table 7.4: Data used in the calculation of the 1995 event discharges at Raise Beck (Cross section 18 is two channels either side of a large in channel bar, hence it is divided into the right bank channel [RB] and the left bank channel [LB])

Deposit	Cross sections	Mean max. Cap. (m^2)	Mean min. Cap.(m^2)	Velocity (1)($m\ s^{-1}$)	Velocity (8)($m\ s^{-1}$)	Q(1max) ($m^3\ s^{-1}$)	Q(1 min) ($m^3\ s^{-1}$)	Q(8 max) ($m^3\ s^{-1}$)	Q(8 min) ($m^3\ s^{-1}$)
9	15, 16	4.90	3.99	2.61	1.73	12.78	10.39	8.46	6.88
10	15, 16	4.90	3.99	3.70	1.73	18.13	14.74	8.46	6.88
11	15, 16	4.90	3.99	3.54	1.73	17.37	14.12	8.46	6.88
12	16, 17	11.68	6.32	3.90	2.24	45.5	24.62	26.22	14.18
13	17, 18^{RB}	14.86	10.50	4.98	2.56	74.03	52.31	38.05	26.89
14	17, 18^{LB}	10.78	6.07	4.88	2.32	52.61	29.61	24.99	14.06
15	18^{RB}, 19	10.02	8.81	3.31	2.12	33.13	29.12	21.21	18.65
16	19, 20	10.74	9.07	5.13	2.38	55.06	46.51	25.52	21.56
21	27, 28	15.00	10.90	4.91	2.03	73.58	53.46	30.45	22.12
22	28, 29	13.54	11.34	5.52	1.72	74.71	62.54	23.33	19.53

<u>Figure 7.10:</u> Reconstructed discharges of the 1995 flood event at Raise Beck (Dotted line symbolises the location of the fan apex)



maximum discharge, the 1995 flood peaked at between 26.89 $m^3 s^{-1}$ and 74.03 $m^3 s^{-1}$.

To compare these discharge values with other palaeohydrological discharge reconstructions in the UK, variable size catchment areas need to be accounted for. Specific discharge is an appropriate measure as it standardises the discharge to a unit area ($m^3 s^{-1} km^{-2}$). In the case of Raise Beck, palaeohydrological specific discharges range between 22.32 and 61.44 $m^3 s^{-1} km^{-2}$ (catchment area = 1.205 km^2, Q = 26.89 $m^3 s^{-1}$ and 74.03 $m^3 s^{-1}$). These values are similar to a flood at Redacre Gill (Warburton, 1983): 60.58 $m^3 s^{-1} km^{-2}$ (catchment area = 1.2 km^2, Q = 72.7 $m^3 s^{-1}$), and also the lower estimate for the 1749 flood of Mosedale Beck (Carling, 1997): 25 $m^3 s^{-1} km^{-2}$. They are greater than reconstructed values for flooding at Glenridding Beck in 1927 (Carling and Glaister, 1987): 9.55 $m^3 s^{-1} km^{-2}$ (catchment area = 10.45 km^2, Q = 99.8 $m^3 s^{-1}$), and similarly larger than values for the Allt Mor flood of 1978 (McEwen and Werritty, 1988): 4.09- 4.94 $m^3 s^{-1} km^{-2}$ (catchment area = 16.4 km^2, Q = 67- 81 $m^3 s^{-1}$). Therefore in these comparisons the 1995 flood of Raise Beck is shown to be significant, though not a unique occurrence for British upland streams.

7.5.4 Discussion of the various reconstructions of the 1995 flood event at Raise Beck

An order of magnitude difference exists between the rational method (5.56 $m^3 s^{-1}$) and the value range of 26.89 $m^3 s^{-1}$ to 74.03 $m^3 s^{-1}$ calculated using palaeohydrological approaches. Shaw (1994) suggests that the rational approach can provide a rough first estimate, especially in small impervious catchments, as is the case here. Therefore it is suggested that the palaeohydrological approaches may be overestimating the peak discharge, though this has to be viewed in context of the limitations of the rational approach. These limitations include a constant runoff coefficient (Kirkby *et al.*, 1993), the assumption that rainfall is constant during the period prior to T_c and that all the rainfall contributes to the flow (Shaw, 1994.) A further problem at Raise Beck and in other small steep upland catchments is that the T_c is less than the rainfall recording interval of one hour, therefore it is possible that hourly rainfall intensities based on observations of intensity over a period of less than one hour will exceed the 17.5 mm h^{-1} value used. A higher value of rainfall intensity would increase the discharge, but only by a small amount. For example, an arbitrary increase in the intensity to 25 mm h^{-1}, only raises the discharge to 8.13 $m^3 s^{-1}$. However, Burt (2001, *pers. comm.*) contends that if 10 mm of the 17.5 mm fell within 10 minutes (similar to the T_c period), the hourly equivalent would be 60 mm h^{-1}, and such a rainfall intensity would produce a discharge of 19.52 $m^3 s^{-1}$. This is unlikely, as illustrated by an example from the Iron Crag rain gauge. Here, a frontal rainstorm on the 28th November 1999 (see Figure 5.24) peaked at 9.7 mm h^{-1}, with maximum 20, 10 and 5 minute totals being 4.8, 3, and 1.8 mm respectively. The 10 minute rainfall total gives an hourly equivalent of 18 mm h^{-1} (3 mm × 6), hence in this instance the sub-one hour distribution is far less skewed than Burt (2001, *pers comm.*) argues. Therefore, if the storm of the 30th January 1995 at Raise Beck behaved in a similar fashion then the discharge of 19.52 $m^3 s^{-1}$ would be an overestimation. Another limitation of the rational method is the exclusion of the supply of runoff from snowmelt, though in the absence of local records about snow depths it is not possible to calculate the water equivalent that would have been released by melting of the snowpack.

The FEH result of 4.20 $m^3 s^{-1}$ is similar to the value of 5.56 $m^3 s^{-1}$ calculated with the far simpler rational method, and is again an order of magnitude less than the values calculated from the palaeohydraulic techniques. As a continuation of previous comparisons, all values are expressed as maximum specific discharge ($m^3 s^{-1} km^{-2}$) for the point at which discharge is calculated. The rational and FEH methods calculate discharge at the fan apex, a catchment area of 1.27 km^2, whilst the maximum discharges using the palaeohydraulic techniques are reported upstream at boulder deposit 13, a catchment area of 1.205 km^2. The maximum specific discharges are 4.38 $m^3 s^{-1} km^{-2}$, 3.30 $m^3 s^{-1} km^{-2}$, and 22.32 to 61.44 $m^3 s^{-1} km^{-2}$ respectively. When these values are compared to the proposed envelope curves for peak floods in the UK (Werritty and Acreman, 1985; Carling and Glaister, 1987; and Acreman, 1989), it is found that all the estimates of discharge at Raise Beck fall below the envelope defined as the catastrophic flood by Acreman (1989) (Figure 7.11). If the highest estimate of the specific discharge at Raise Beck were accepted, it would be the highest reconstructed value for a catchment of the size of Raise Beck in the UK. In contrast, the lower estimates from the rainfall-runoff approaches would fall below the normal maximum flood curve if this was extrapolated to the smallest catchments. Although there are uncertainties in rainfall-runoff and palaeohydraulic techniques, rainfall-runoff is considered superior as it uses raw data and makes fewer assumptions. Therefore it can be concluded that the palaeohydraulic approaches tend to overestimate the discharge, especially in small-steep catchments such as Raise Beck.

7.5.5 Geomorphological responses and channel change

A comparison of pre-flood and post-flood aerial photographs allows responses to the 1995 flood to be identified. The poor quality of the 1988 photograph means it is difficult to fully interpret; therefore the 1983 photograph is used as the pre-flood benchmark as it is of better quality. Figure 7.12 shows the main geomorphological features identified from the aerial photographs in 1983 and 1995. The numerical annotations highlight areas and features where significant change has occurred. Labels 1-5 are natural impacts attributable to the flood, whilst 6 and 7 are engineering responses. Label 1 indicates a shallow landslide on the left bank side of the main channel between cross sections 21 and 22. This was the only fresh hillslope failure occurring during the flood. Label 2 indicates the major reworking of the channel deposits from the head of Reach 3 downwards. This becomes more pronounced downstream of cross section 21(Figure 7.2) where large accumulations of deposits occur in an area of reduced hillslope confinement and lower channel gradient. Some of this apparent reworking may be due to the scour of rocks in the flood. Label 3 shows the flood has slightly reduced the sinuosity of the channel. Label 4 identifies the deposit associated with the channel avulsion, and label 5 locates the 1995 fan deposit adjacent to the A591. Both of these deposits were unmodified in the engineering that followed the flood. The area of these deposits prior to the flood was 6400m^2. Post-flood the area of the channel deposit was approximately 8650 m^2; an increase of 2250 m^2. Of this enlargement the new fan accounts for 1600 m^2 or 70 % of all the change. Hence the change in channel deposit area is less significant than might be first thought. In regard to the fresh fan deposit, five shallow pits dug from the apex to the avalanche toe indicate a well sorted, locally imbricated and fining up sediment, indicative of fluvial processes (Costa, 1988). As previously stated, following the flood, North West Water channelised the flow using riprap boulders and backfilling, allowing the path below the left bank

Figure 7.11: Envelopes of maximum specific discharge against drainage area adapted from Acreman (1989) (Curve A-A defines the Normal Maximum Flood in upland catchments, based on empirical data from the Interim Report of the Committee on Floods in relation to Reservoir Practice of 1933, updated in 1960 by the Institution of Civil Engineers. Curve B-B is the catastrophic curve, also introduced in 1960, and is based on statistical theory). With estimated specific discharges of Helvellyn Massif floods plotted, i.e. Raise Beck (1995, this study), Glenridding Beck 1927 (Carling & Glaister, 1987), and Mosedale Beck, 1749 (Carling, 1997)

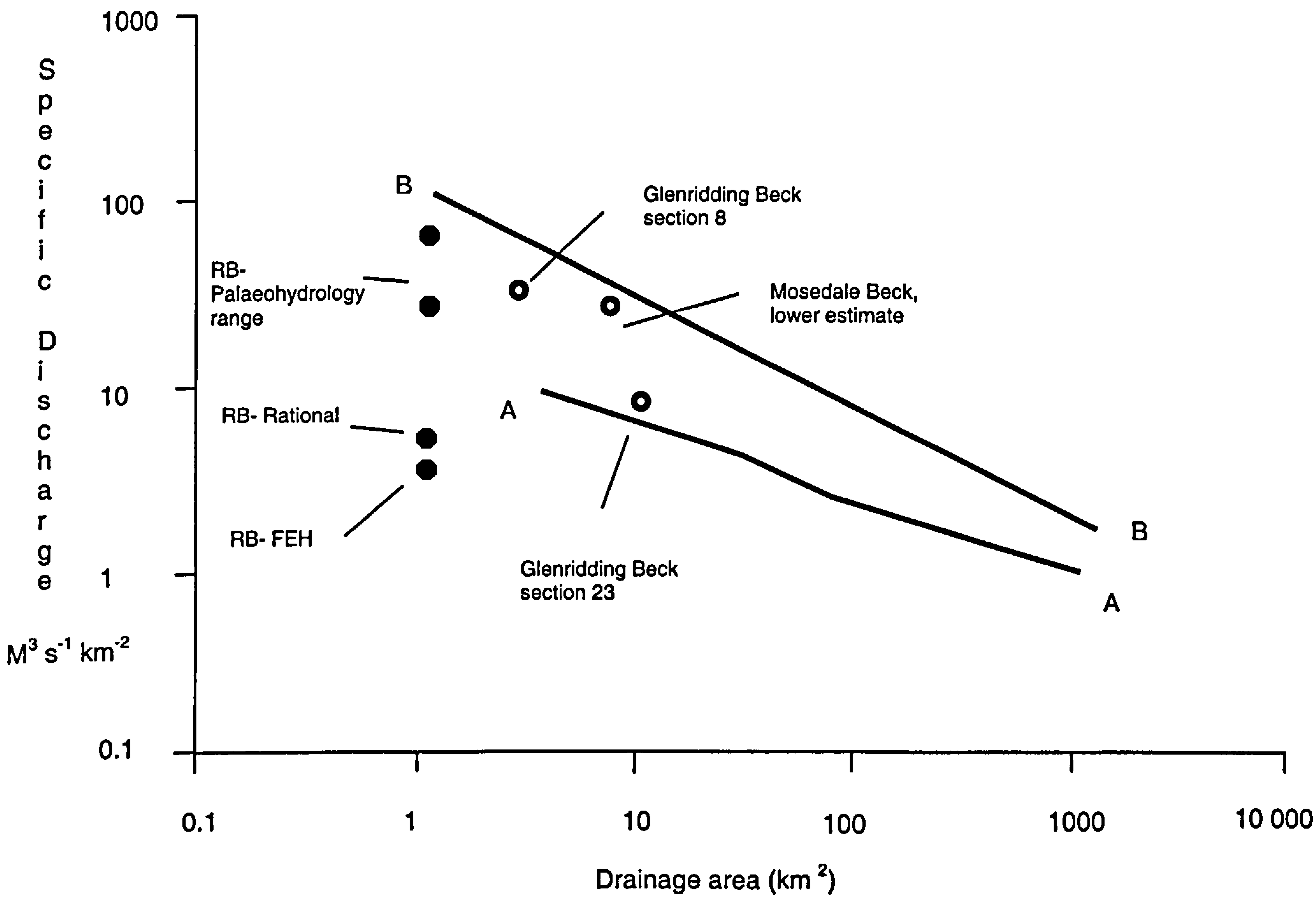
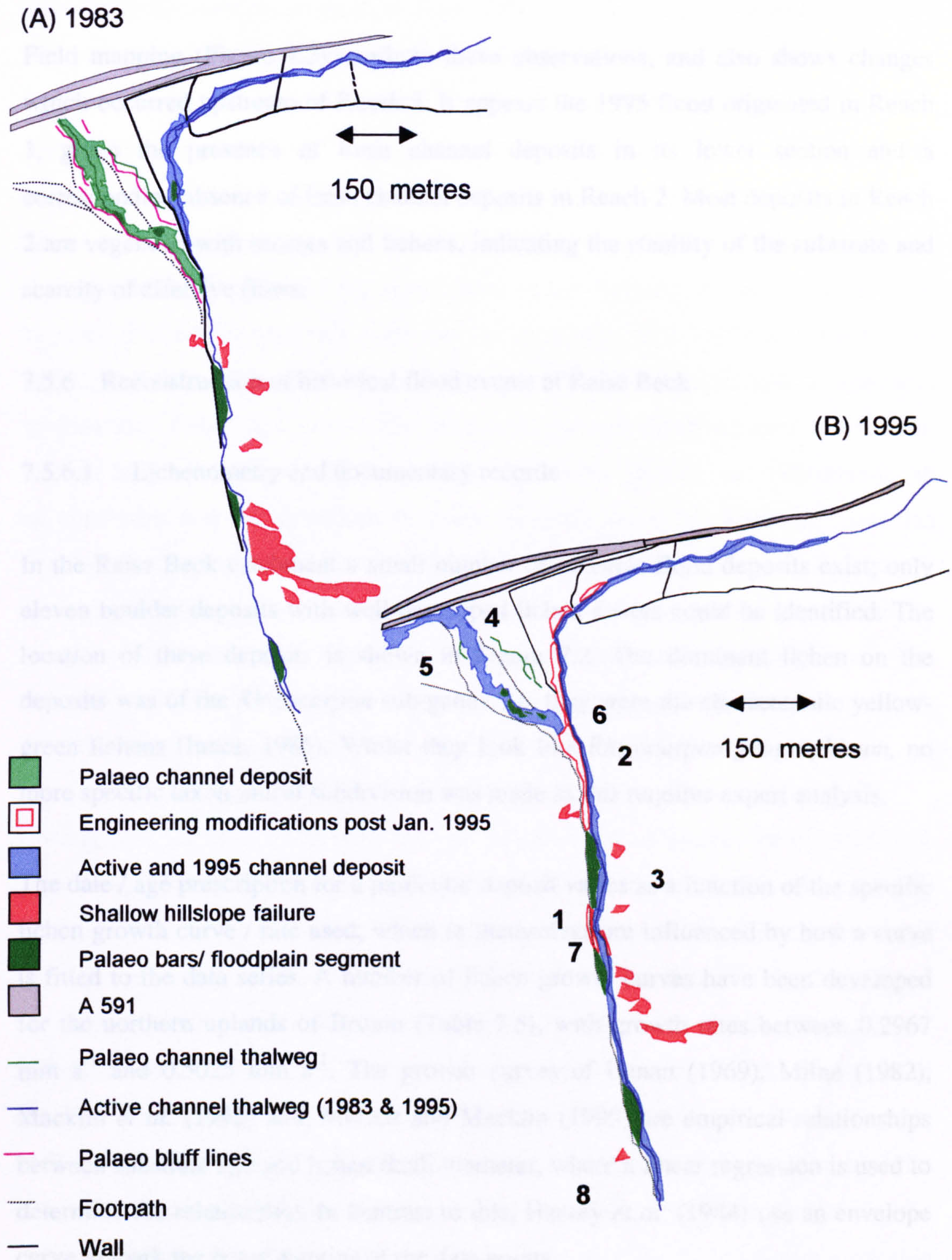


Figure 7.12: A comparison of the main geomorphological features at Raise Beck, (A) prior to the January 1995 flood, 10.8.83, & (B) following the January 1995 flood, 25.7.95. Annotations highlight features outlined in the text.



hillslope failure to be reinstated (Label 7) and to direct the water into Reach 4 (Label 6). Label 8 shows a small hillslope failure which did not occur as a result of the 1995 flood, but between 1983 and 1988, which explains its presence on the 1995 diagram but not the 1983 diagram.

Field mapping (Figure 7.2) confirms these observations, and also shows changes which occurred upstream of Reach 3. It appears the 1995 flood originated in Reach 1, given the presence of fresh channel deposits in its lower section and a corresponding absence of fresh channel deposits in Reach 2. Most deposits in Reach 2 are vegetated with mosses and lichens, indicating the stability of the substrate and scarcity of effective flows.

7.5.6 Reconstruction of historical flood events at Raise Beck

7.5.6.1 Lichenometry and documentary records

In the Raise Beck catchment a small number of dateable flood deposits exist; only eleven boulder deposits with well developed lichen covers could be identified. The location of these deposits is shown in Figure 7.2. The dominant lichen on the deposits was of the *Rhizocarpon* sub-genus, i.e. they were the characteristic yellow-green lichens (Innes, 1985). Whilst they look like *Rhizocarpon geographicum,* no more specific taxonomical subdivision was made as this requires expert analysis.

The date / age prescription for a particular deposit varies as a function of the specific lichen growth curve / rate used, which in themselves are influenced by how a curve is fitted to the data series. A number of lichen growth curves have been developed for the northern uplands of Britain (Table 7.5), with growth rates between 0.2967 mm a^{-1} and 0.5025 mm a^{-1}. The growth curves of Lunan (1969), Milne (1982), Macklin *et al.* (1992) and, Merrett and Macklin (1999) are empirical relationships between substrate age and lichen thalli diameter, where a linear regression is used to determine the relationship. In contrast to this, Harvey *et al.* (1984) use an envelope curve to mark the outer margins of the data points.

To investigate the impact of the different positioning of envelope and linear lichen growth rate curves, an envelope curve was added to the Merrett and Macklin (1999) data, which was originally published with just a linear curve. Using these two curves and the mean of the largest five lichen thalli on each of the Raise Beck boulder deposits differences in deposit age were calculated. The age prescribed to boulder deposits varied between 49 and 91 years as a function of the different curve locations. In performing this comparison, the ages derived from the envelope curve were achieved graphically. In contrast ages from the linear curve were calculated using the linear growth rate. It is therefore possible that some of the age difference between the previous envelope and linear curve comparison results from these different methods. To check the significance of this hypothesis, ages of Raise Beck boulder deposits determined from the linear growth rate curve of Merrett and Macklin (1999) were calculated using both the growth rate and a graphical interception of the linear curve. The graphical approach produced ages that were at worst 2 to 3 years different to those obtained using the growth rate. Therefore it can be concluded that the deviations between age estimates result from the linear and envelope curves and not the method of calculation. With the envelope curve providing a maximum age (assuming that the data defining the envelope location are not anomalously large lichens) and the linear approach provides an age estimate less than the maximum age (but one which is more characteristic of the lichen sample used to create the linear curve).

Carling and Glaister (1987) used the envelope curve of Harvey *et al.* (1984) to provide ages for the lichen-covered boulders in Glenridding Beck. It is stated that the mean of the five largest lichens was 53 mm (measured in 1986), which gave an age of 62 years, i.e. a date of 1924. This coincides closely with Hay (1928) who mapped the large boulder deposits after the flood in 1927, suggesting that the Harvey *et al.* (1984) curve provided a good estimate of deposit age. However, if the growth rates from the linear curves in Table 7.5 are used, ages between 105 and 178 years result, and some of these other curves have independent validation. For example, Macklin *et al.* (1992) validated their lichen curve by dating substrates of known age, and the differences between predicted and actual age were very small. No obvious solution can be provided for this contradictory evidence. Two options exist, either to use the

Table 7.5: Lichen growth curves and rates for northern uplands, for *Rhizocarpon.* (Authors cite lichen to be *Rhizocarpon geographicum.*) (* Data modified and rates derived by authors)

Author	Area	No. sites/ lichens	Substrate Lithology	Curve type	Mean annual rate (mm a^{-1})
Lunan (1969)*	Lake District	22/105	Sandstone	Linear	0.2967
			Slate	Linear	0.3162
			Granite	Linear	0.3952
Topham (1977)	Argyllshire	1/?	Granite	?	0.5025
Milne (1982)	Northumberland	2/?	?	Linear	0.32
Harvey *et al.* (1984)	Howgill Fells	6/94	?	Envelope	c. 0.4
Macklin *et al.* (1992)	North Pennines	18/250	Sandstone	Linear	0.39
Merrett & Macklin (1999)	Yorkshire Dales	32/129	Sandstone	Linear	0.36

locally validated lichen curve of Harvey *et al.* (1984) or a range of linear curves which broadly agree and include lichen curves specific to the Lake District. At Raise Beck the second option is adopted, and dating is based on the mean of the five largest lichen diameters for each deposit, with the rejection of the largest thalli if it was 10% or greater in diameter than the second largest thalli on the deposit. This filtering rule of Hodgson (1978) was applied to remove anomalously large thalli, which were found in deposits L4, L6 and L8 (see Figure 7.2 for locations). Table 7.6 outlines the possible ages of Raise Beck boulder deposits using the selected approach and growth rates.

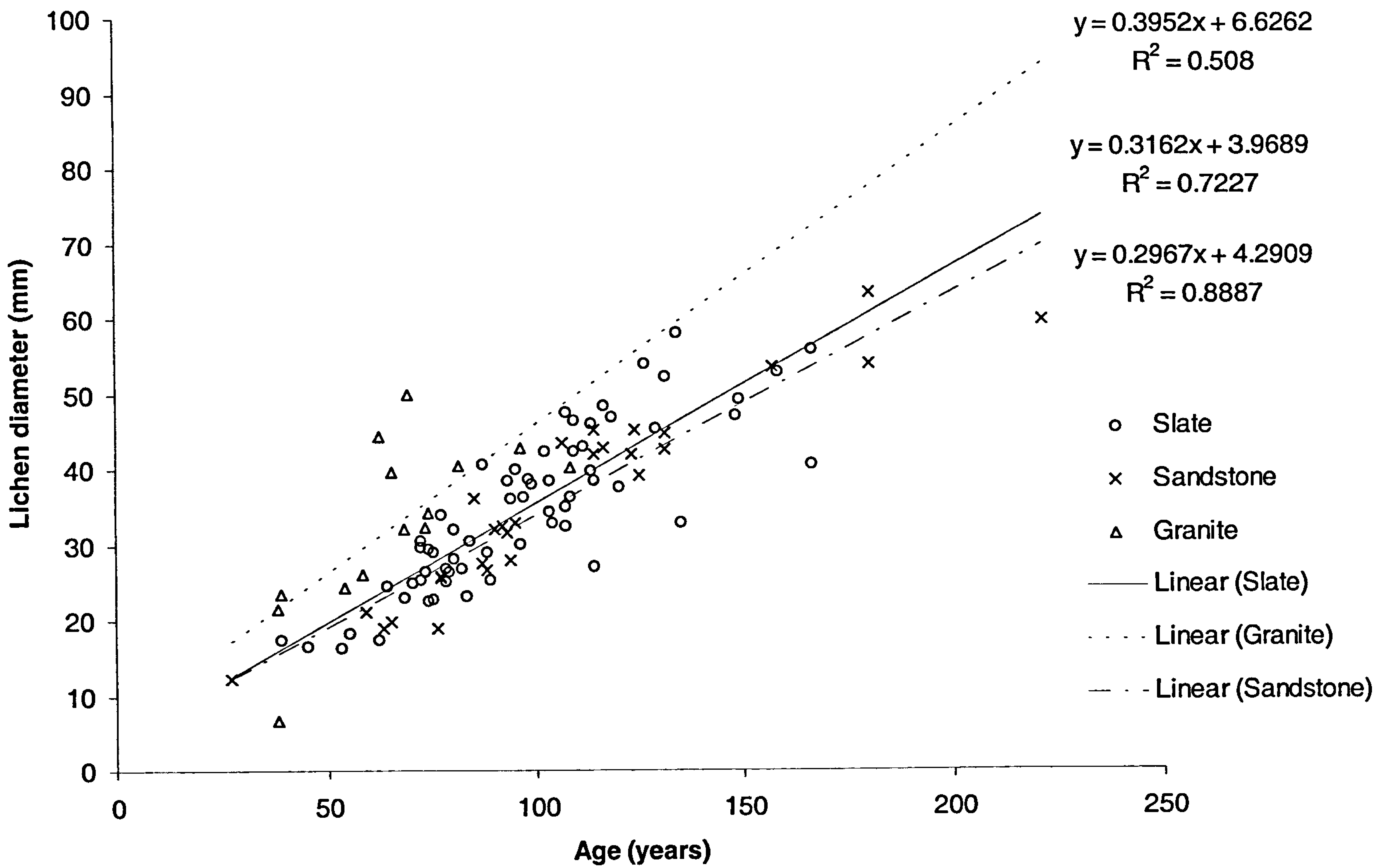
As indicated by Table 7.5 the growth rates are based on different substrate lithologies which have different textural and chemical characteristics. This has a bearing on the lichen growth rate. Innes (1983a) shows that acidic igneous rocks, e.g. granite, have faster growth rate curves than basic igneous rocks, slate and sandstone. Lunan (1969) shows that granite gravestones have the fastest growth rate in the Lake District (0.3952 mm a^{-1}), greater than both sandstone and slate (Figure 7.13), although this growth rate is based on a small data set (n=14). As the substrate at Raise Beck is andesitic tuffs, of an intermediate to slightly acidic composition, it is necessary to apply the most appropriate growth rates. The mineralogy of andesite includes feldspar, biotite, mica, hornblende and pyroxene (Hamilton *et al.*, 1998). Granite is composed of quartz, feldspar, biotite and hornblende. Some of these minerals also occur in sandstone. Carrara and Andrews (1973) graphically show *Rhizocarpon geographicum* growth variations with lithology in Colorado, where the size of lichens on andesitic boulders were similar to the size of lichens on both sandstone and granite boulders. Therefore the growth curves relating to granite and sandstone seem most relevant to the dating of lichens at Raise Beck. This selection takes no account of the other geographical and ecological factors listed by Innes (1985), which affect lichen growth rates.

Thus the final growth rate curves used at Raise Beck are Lunan (1969) sandstone (0.2967 mm a^{-1}), granite (0.3952 mm a^{-1}), Macklin *et al.* (1992) sandstone (0.39 mm a^{-1}), and Merrett and Macklin (1999) sandstone (0.36 mm a^{-1}). The growth rate of Topham (1977) for granite is not included as insufficient detail is provided. Figure 7.14 shows the age estimates of the Raise Beck deposits. The maximum values are

Table 7.6: Age of Raise Beck deposits using a range of linear growth rates. (Rate in mm per year; age in years)

Detail	Rate	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11
Mean 5 Largest (mm)	-	38.8	31.8	47.8	52.8	47.0	55.8	49.2	51.4	50.2	25.2	53.4
Lunan (1969)	0.3162	122.7	100.6	151.2	167.0	148.6	176.5	155.6	162.6	158.8	79.7	168.9
	0.2967	130.8	107.2	161.1	178.0	158.4	188.1	165.8	173.2	169.2	84.9	180.0
	0.3952	98.2	80.5	121.0	133.6	118.9	141.2	124.5	130.1	127.0	63.8	135.1
Macklin *et al.* (1992)	0.39	99.5	81.5	122.6	135.4	120.5	143.1	126.2	131.8	128.7	64.6	136.9
Merrett & Macklin (1999)	0.36	107.8	88.3	132.8	146.7	130.6	155.0	136.7	142.8	139.4	70.0	148.3

Figure 7.13: Lichen size age curves for the Lake District (Lunan 1969)

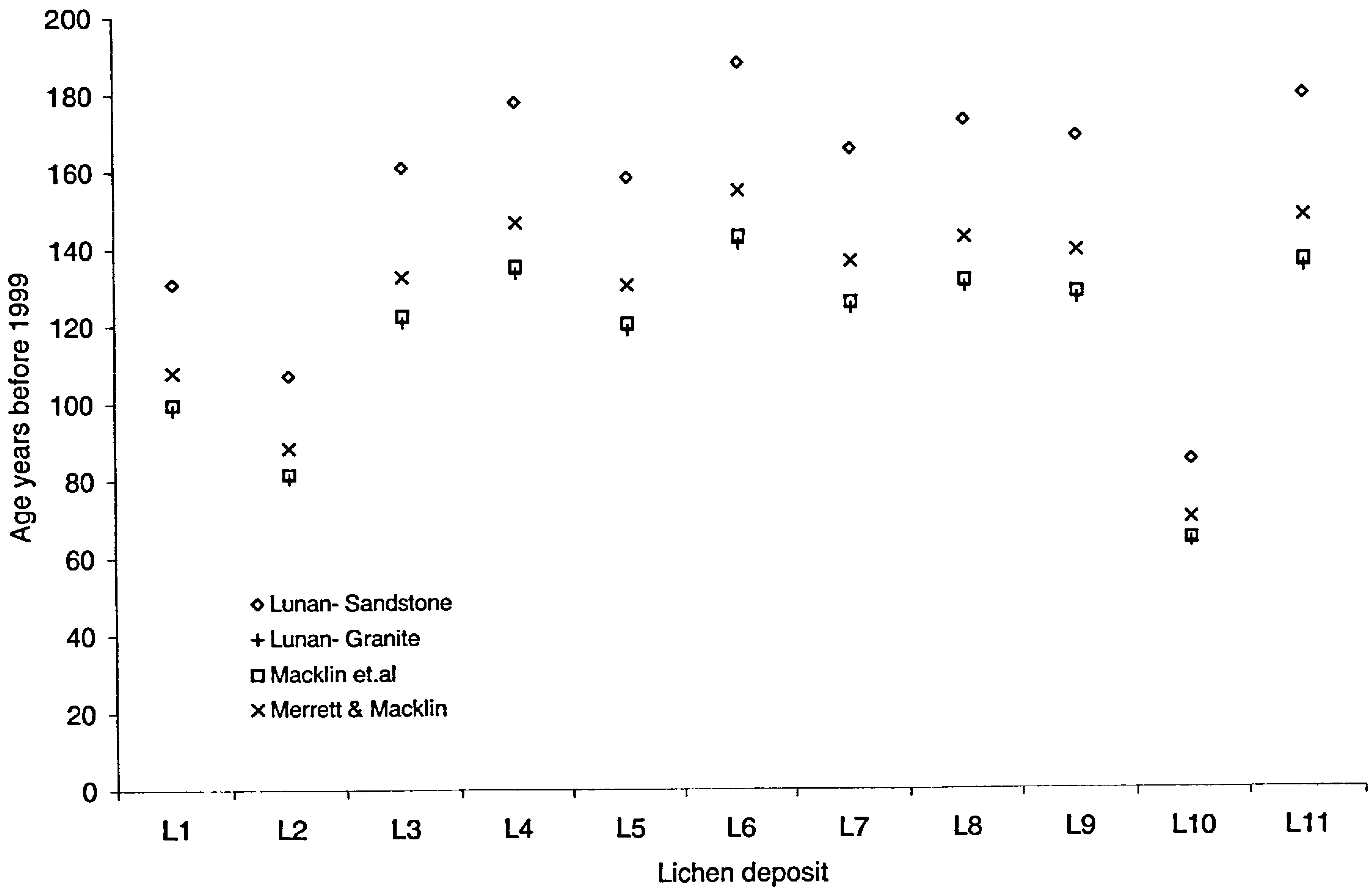


from Lunan's (1969) sandstone growth rate, which has biased the age range upward. The remaining three values provide similar estimates of age, and therefore this smaller range is taken as the best estimate for the ages of lichens on boulder deposits. No correction for the lag time between boulder deposition and lichen colonisation is made, as this variable is inherent in the lichen size age curves from which the growth rates are derived. Further, the scatter of size-age (see for example Figure 7.13) relations exceeds the likely lag time of colonisation. Calkin and Ellis (1980) state that the lag time is a function of climate; in the Arctic it ranges from 10 to 50 years, but in reference to Highland Scotland, Innes (1983a) states eight years.

Visually it appears that the ages of the Raise Beck boulders can be grouped into four or five flood deposits (Figure 7.14). Lichen deposits L1, L2 and L10 appear to be single events, with ages in the ranges: 108 to 98 years (1891 to 1901); 88-80 years (1911 to 1919); and 70 to 64 years (1929 to 1935) respectively. Lichen deposits L1 and L2 are situated before Reach 3, and therefore precede the main flood deposits that follow downstream. Deposit L1 may have been formed by the flood of November, 1898 (Kelbarrow, 1898), though the range in the lichen date for L1 makes this uncertain. These deposits indicate that floods capable of cobble and boulder transport can be generated in the headwater areas of the catchment. Lichen deposit L10 is on old flood bars in Reach 4 prior to the confluence with Birkside Gill (Figure 7.2). The absence of other deposits in this channel may reflect engineering works carried out and burial by active gravel deposits. The timing of this event is similar in age to the Glenridding Beck deposits (Carling and Glaister, 1987) and is coincident with the observation of Huddleston (1935) that Raise Beck was diverted to Thirlmere by a flood a few years prior to 1935.

The most important lichen-dated deposits are those on the bars and floodplain segments in Reach 3 and the upper part of Reach 4. It is possible that lichen deposits (L3, L4, L5, L6, L7, L8, L9, L11) all relate to one flood event and the scatter between the prescribed ages is a function of different lichen colonisation times resulting from the local environmental factors affecting each deposit. If this scenario is accepted the deposits would relate to an event 155 to 119 years prior to 1999, i.e. 1844 to 1880. This age band of 36 years seems broad, therefore a more subtle

Figure 7.14: The ages of Raise Beck boulder deposits, based on the variability from the selected growth rates.



division would be two deposits, the older one being lichens L4 (147 to 134 years), L6 (155 to 141 years), L8 (143 to 130 years), and L11 (148 to 135) years, therefore providing a date in the range 1844 to 1869. The First Edition six-inch Ordnance Survey map, surveyed in 1859, tends to suggest that the flood bar and floodplain segment containing lichens L4 and L6 existed at this time. The Second Edition six-inch Ordnance Survey map published in 1900, shows the planform and surrounding floodplain segments in the areas of L4 and L6 to be identical. The additional cartographic detail of the Second Edition shows these identical areas to be composed of large boulders. Therefore on the basis of this cartographic evidence this flood unit can be bracketed more precisely between 1844 and 1859.

The second, younger deposit is composed of lichens L3 (133-121 years), L5 (131-119 years), L7 (137-124 years), and L9 (139 to 127 years), indicating a date between 1860 and 1880. Deposit L9 is situated in Reach 4. However, it is known with the exception of the November 1898 flood, that Raise Beck flowed south from the fan apex until at least c. 1935. Therefore the presence of a flood deposit of between 139 and 127 years at this location fails to fit the constructed history of Raise Beck. This suggests the impact of historical floods was beyond the boundaries of the historical channel course.

The scenario of two main flood deposits provides more acceptable date ranges, the older deposit spanning 15 years and the younger deposit over 20 years. In summary, five tentative flood units have been identified by lichenometry and documentary evidence at Raise Beck, these are outlined in Table 7.7. Deposits for events prior to 1844 do not exist, three possible explanations include: that the deposits have been destroyed by these subsequent events including the 1995 flood; a stable substrate surface is likely to have been revegetated, as most of the flood units identified are largely covered in grass; and engineering modifications of the channel are a further cause of disturbance.

Table 7.7: Raise Beck Flood units. (The underlined date is provided by the Ordnance Survey First Edition six Inch map.)

Flood Unit	Lichen deposits	Ages years (Highest mean to lowest minimum)	Date Range Relative to 1999
1	L4, L6, L8, L11	155-130	1844-1859
2	L3, L5, L7, L9	139-119	1860-1880
3	L1	108-98	1891-1901
4	L2	88-80	1911-1919
5	L10	70-64	1929-1935

A climatic proxy, i.e. rainfall, provides a check on the validity of these flood unit dates in the absence of historical stream gauging and precise documentary evidence. McEwen (1987) states hydrological records can be used to augment and check flood chronologies in upland basins. However the relationship between rainfall and flooding is not as straightforward as often assumed, owing to runoff responses, seasonality, areal extent of rainfall, etc. Despite these complications general trends can still be identified from a smoothed data series.

Robson *et al.* (1998) consider the link between climate and floods for the whole of the UK between 1870 and 1990. Having noted the lack of reliability in older data and the changing distribution of the flood and rain gauge networks, the number of floods per year based on the Institute of Hydrology peak-over-threshold data and monthly rainfall broadly correspond. It is stated that a significant positive correlation exists, of which the most significant peak in the relationship is approximately 1870 to 1885. Lower peak apexes occur in 1915, 1930 and 1940.

Jones and Conway (1997), following Wigley *et al.* (1984), Wigley and Jones (1987) and Gregory *et al.* (1991), consider the variability in UK rainfall on an area-averaged basis, i.e. regional and national precipitation series. The regional composite smoothed for England and Wales 1766- 1995 presented by Jones and Conway (1997) shows wetter peaks in 1840, 1848, 1860, 1866, 1877, 1903, 1914, 1927 and 1937. Over the 1840 to 1940 timespan prolonged periods of greater wetness were 1870 to 1886, 1910 to 1920, and 1920 to 1933, a high level of agreement with the trends for the entire UK data set (Robson *et al.*, 1998).

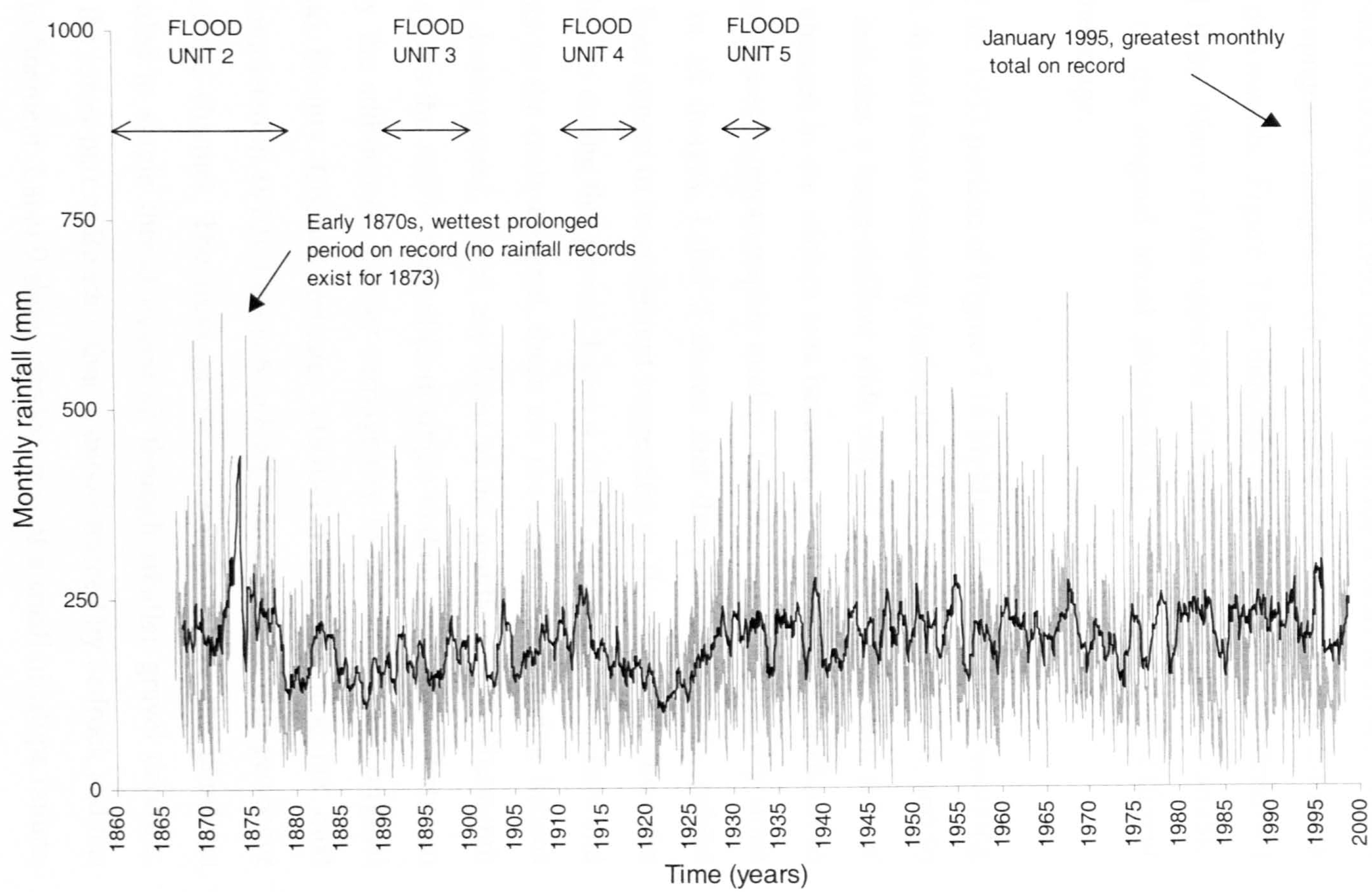
With reference to the North Pennines Macklin *et al.* (1992), and Rumsby & Macklin (1994) reiterate these wet periods for Northern England, most specifically the 1840 to 1880 and 1920 to 1950 time periods, with increased flood frequency and magnitude on the River Tyne. This relates to zonal and meridional climatic regimes, which give higher precipitation totals (Rumsby and Macklin, 1994).

Local rainfall records are provided by the Helvellyn Birkside rain gauge (c.1 km to the north of Raise Beck). This monthly rain gauge record (Figure 7.15) began in September 1866 and continues to the current day. The data series is composed of rainfall readings from a series of rain gauges in slightly different locations over the time of the record, according to the operator of the rain gauge and following suggestions to improve the accuracy of the gauge collection. The record shows many individual monthly peaks, though wetter periods indicated by higher sustained values of the running mean are prior to 1880; 1908-1913; and 1928 to 1939. So once again similar to the broader trends identified for the whole of the UK.

The correspondence of the reconstructed ages of the Raise Beck flood deposits to these past climatic trends are similar. Flood units 1 and 2 fall within the period of increased rainfall and flood frequency (1840 to 1880). Deposit 4 and 5 fit the rainfall and flood peak periods identified by Robson *et al.* (1998) and Jones and Conway (1997), and the Helvellyn Birkside data. There is a poorer correspondence for deposit 3, which occurs in an intermediate climatic phase of less precipitation and flood frequency (Rumsby and Macklin, 1994). These broad climatic trends provide general support to the lichenometric results but do not validate them, as annual and monthly rainfall totals can still mask the effect of individual storms that may be responsible for the flood units. Furthermore, it should not be forgotten that Raise Beck is a small mountain catchment susceptible to local storm events (especially convective) that may be independent of regional or national trends.

Deposits 1 and 2 are evidence that events following 1880 have so far not been as geomorphologically effective across the whole of Raise Beck as those events prior to 1880. The implication of this is that the floods responsible for deposits 1 and 2 were of greater magnitude and lower frequency (compared to current conditions) than the flood of 1995. Therefore the 1995 event, though significant, had a more local impact

Figure 7.15: Historical monthly rainfall at Helvellyn Birkside, with 12 month moving average. Data series constructed from Meteorological Office Archive records. These indicate the movement and replacement of rain gauges in 1877, 1925 and 1931. Therefore the positioning and gauge type has not been consistent throughout the data series. The absence of data in 1873 accounts for the high value of the running mean.



in the lower reaches of the third order channel and around the fan apex.

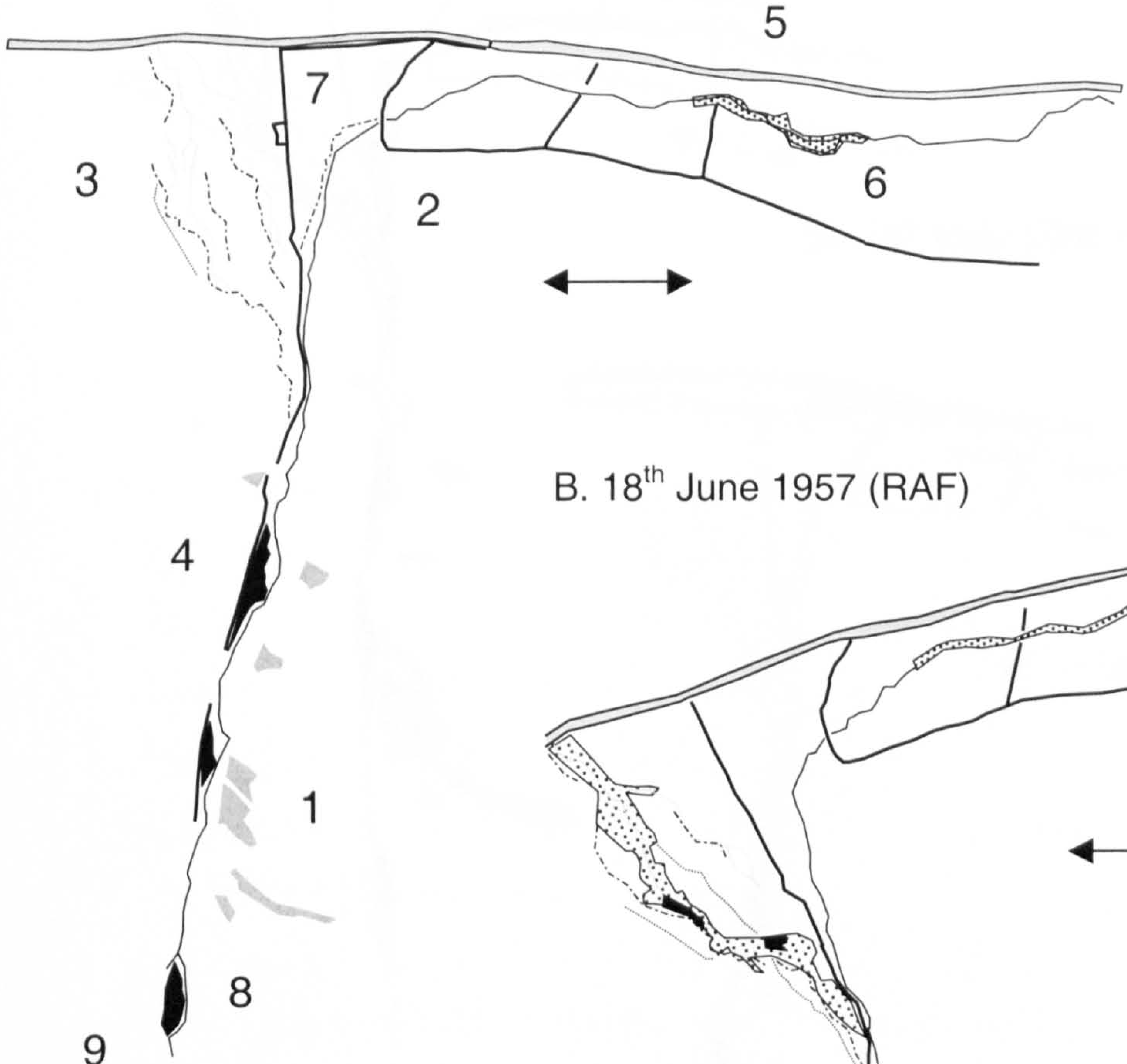
7.5.6.2 Aerial photography

Aerial photographs of Raise Beck taken in 1953 (RAF), 1957 (RAF), 1983 (ADAS/MAFF), 1988 (ADAS) and 1995 (ADAS), provide a short historical record of natural and anthropogenic changes in the catchment, most specifically from the head of Reach 3 downwards. Figure 7.16 illustrates the main features identified between 1953 and 1988. Many of the apparent differences are due to the variable quality and scale of the original aerial photographs, which leads to different interpretations of the image.

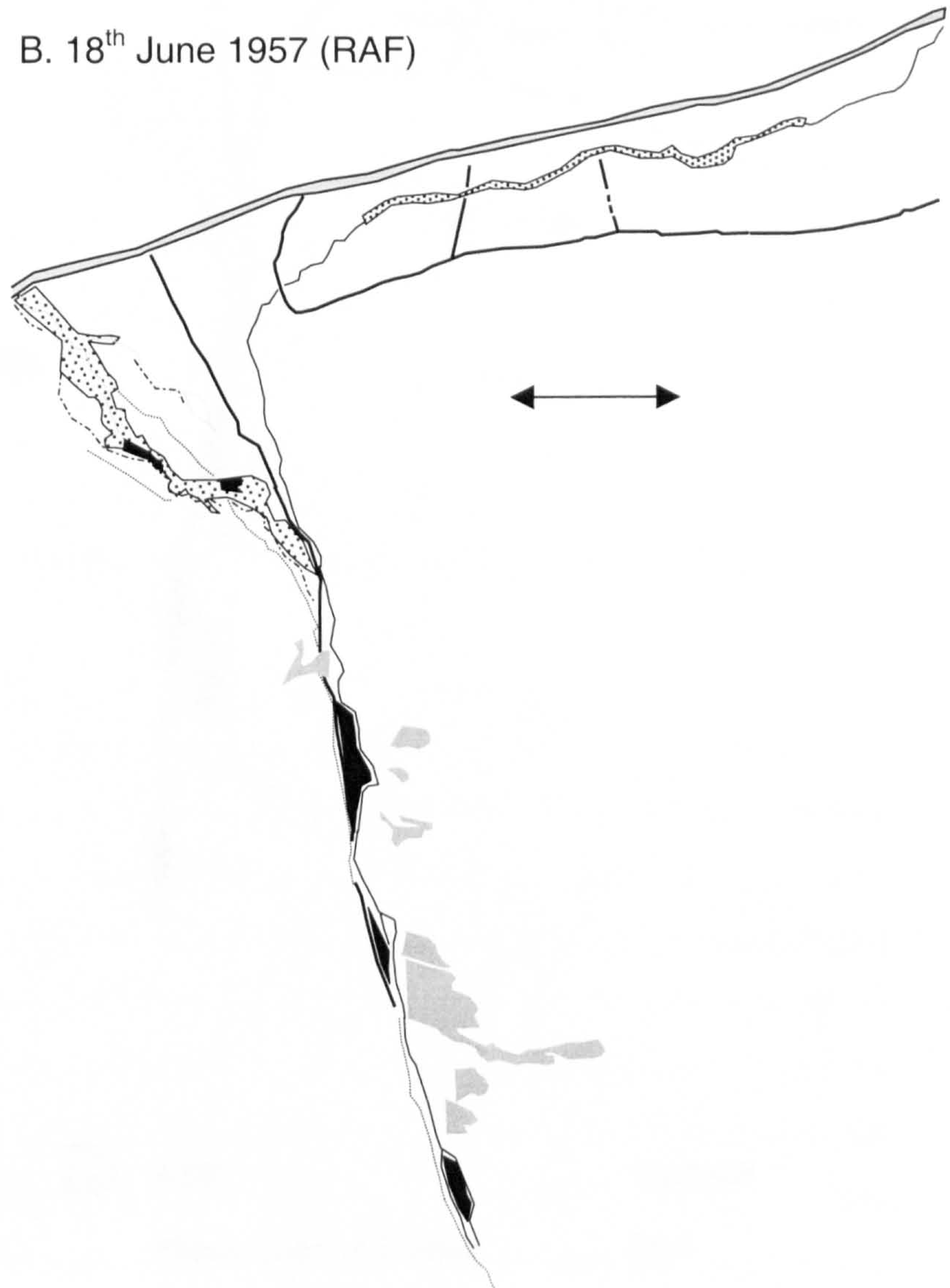
The annotations of the 1953 portion of Figure 7.16 highlight features both remaining constant (1, 2, 3, & 4) and those changing during the 1953 to 1988 (5, 6, 7, 8, and 9) timespan. Label 1 indicates a large shallow slide deposit on the right bank side of Reach 3. Specific changes in the surface area between the diagrams are difficult to interpret due to differences in photographic quality. Label 2 indicates that dry stone walls are present in all images. Label 3 shows that the palaeo-channels, palaeo deposits and bluff lines appear to be consistent suggesting no flow of water down the left bank side of the fan during this period. Label 4 marks the large palaeo bars and floodplain segments in the main channel, these are the deposits containing lichens L4, L5, L6 (going downstream), which are dated to the middle of the Nineteenth Century. Label 5, shows the A591 changed from single to dual carriageway between 1957 and 1983, by the addition of another carriageway to the west of the original road (Westmorland County Council minutes (1970-71) indicate that the dual carriageway was completed in 1970). Labels 6 to 8 all indicate where changes occur in the planform of the channel. The most active zone is 6, where the planform changes from braided to single thread migrating through smaller gravel deposits. This is situated in the lower part of Reach 4 that is unconstrained by bedrock and has limited hillslope confinement. Label 9 shows the location of a small hillslope failure, which as previously stated occurred between 1983 and 1988.

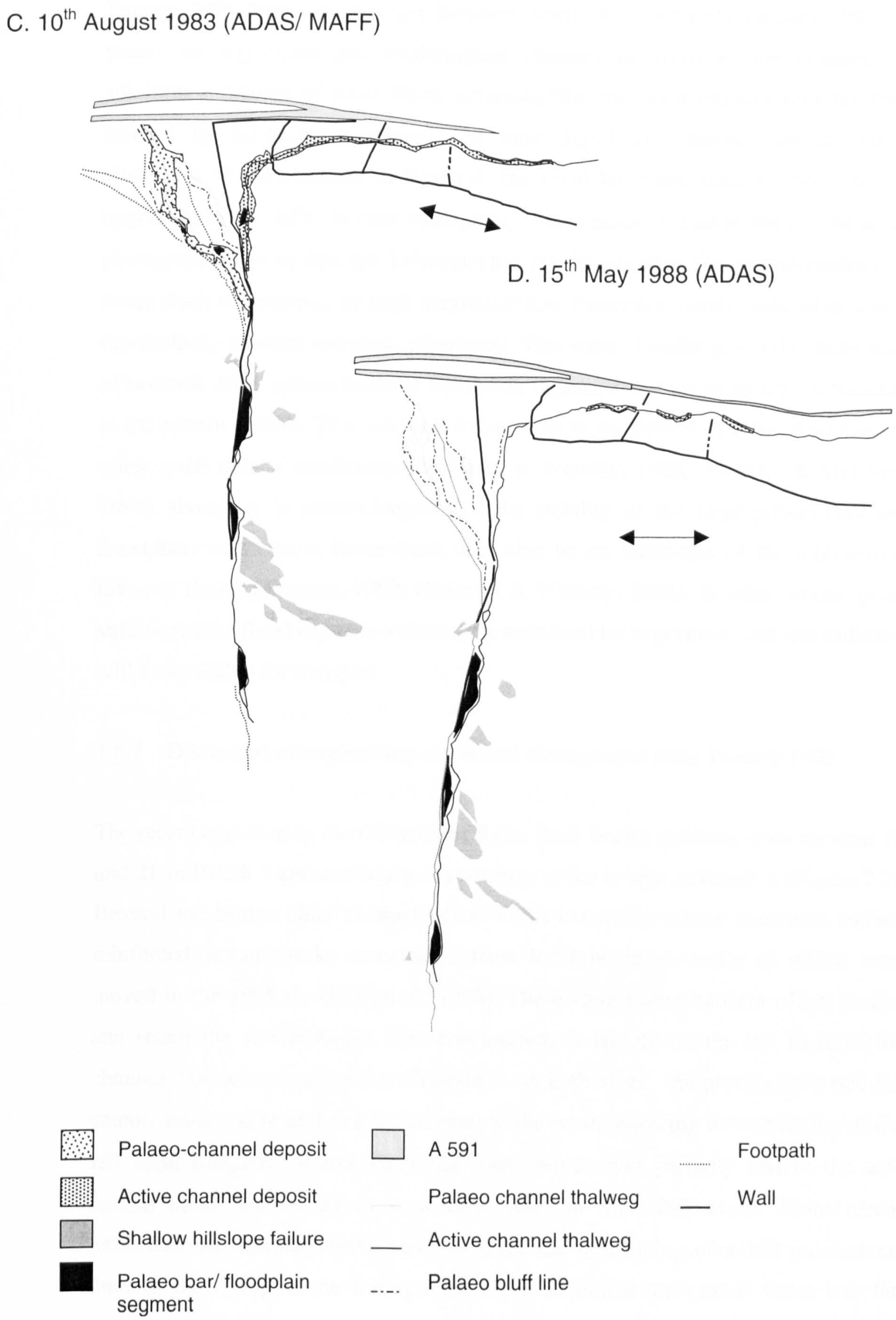
Figure 7.16: Raise Beck geomorphological features derived from aerial photographs (A. 1953, B. 1957, C. 1983, D. 1988) (Scale bar is 150 metres)

A. 21st April 1953 (RAF)



B. 18th June 1957 (RAF)




C. 10th August 1983 (ADAS/ MAFF)
D. 15th May 1988 (ADAS)
Palaeo-channel deposit
Active channel deposit
Shallow hillslope failure
Palaeo bar/ floodplain segment
A 591
Palaeo channel thalweg
Active channel thalweg
Palaeo bluff line
Footpath
Wall

The 1995 diagram has been considered previously with regard to the impact of the January 1995 flood. In summary between April 1953 and early January 1995 (42 years) no significant geomorphological changes occurred in the channels or adjoining hillslopes of Raise Beck, assuming that any flood impacts have not been masked by landscape recovery. The most significant changes are the slight alterations of the planform in Reach 4, the small left bank shallow slide, and the upgrading of the A591 to dual carriageway status across Dunmail Raise. The aerial photograph analysis like the lichenometric results suggests the geomorphology of Raise Beck is governed by high magnitude-low frequency events, indicating a high threshold for channel and slope adjustment. This seems feasible given the dominance of bedrock, large palaeo-bars and floodplain segments and the large size of boulders in the stream system. This conclusion conforms to the pattern of flood responses in other small upland catchments (McEwen & Werritty, 1988, Werritty & McEwen, 1997), though it is acknowledged that the stability of the large palaeo-bars and floodplain segments at Raise Beck may also be an indication of the inter-arrival times of floods (Newson, 1980; McEwen & Werritty, 1988). In other words, given sufficient time flood deposits will become stabilised by vegetation, and less sediment will be available for transport.

7.5.7 Discussion of engineering works and management since January 1995

The recent engineering modification of Raise Beck begins between cross sections 20 and 21 in Reach 3 and continues downstream to the bridge in Reach 4 (Figure 7.2). Beyond the bridge older channelisation works exist. The recent structures include reinforced stream banks constructed from local boulders, many of which were moved in the 1995 flood (Rycroft, 1998). These form riprap barriers which protect and retain the stream banks. The construction is largely on the left bank of the channel, but occasionally channelisation is on both sides. As previously stated the channelisation scheme fixed the channel to the north, allowing the rebuilding of the left bank footpath towards Grisedale Tarn, which was partially lost in the area around cross section 21 to a shallow slide in the 1995 event. More recent modifications (summer 1999) have included the positioning of a 150 mm culvert through the riprap at the fan apex to divert a limited amount of water into the southerly channel. This action was taken following complaints that private water supplies to residents in Grasmere had declined following the re-engineering, which had failed to replace a pipe that existed prior to the 1995 event (Rycroft, 1999).

Figure 7.17 shows the channel capacities at cross sections throughout the Raise Beck catchment. It clearly demonstrates an increase in capacity at the head of Reach 3 after the confluence of the Reach 1 and 2 streams. Following this, channel capacity in Reach 3 continues to increase in size. A Spearman rank correlation coefficient shows there to be a significant positive relationship (r_s 0.509, $p = 0.001$) between channel capacity and distance down stream in the pre-fan section of Reach 3. Figure 7.17 shows two distinct differences in channel capacities at the fan apex. First, there is a reduction in channel capacity between Reach 3 prior to the fan apex, and the channels of lower Reach 3 and Reach 4. Second, the channels after the fan apex are of different sizes. The channel size in lower Reach 3 is of greater capacity than those in Reach 4. However, Figure 7.17 only shows maximum reconstructed channel capacities based on post-flood measurements, making no distinction between cross sections unchanged following the 1995 flood and those that were modified following the event. Figure 7.18 considers this variability by depicting the, maximum and minimum channel capacities calculated for each cross section. It distinguishes reaches, and most importantly, whether the cross section provides evidence of the 1995 flood level, was engineered post 1995, or is a natural channel segment displaying no evidence of 1995 flood levels (classified as other).

A Mann-Whitney U test of the natural and engineered channels in Reach 3 and 4 confirms the interpretation from Figure 7.18, and the alternative hypothesis that natural channels exceed the size of engineered channels. Using the U_x statistic, the null hypothesis was rejected in favour of the alternative hypothesis (0.005 significance level). The difference in the natural and engineered channel capacities is most obvious at the head of the fan between upper Reach 3 and Reach 4. Assuming a flood of similar capacity to the 1995 event, the cross sectional area occupied by water would range between 17.179 m^2 and 23.818 m^2 at cross sections 23 and 24. Cross section 25, although nearer to the fan apex, is discounted as an indicator of the 1995 event at this point in Reach 3 as it was modified by engineering following the 1995 flood. However, immediately downstream of the fan apex engineered cross sections 26 and 31 have maximum capacities of 5.692 m^3 and 9.953 m^3 respectively, and are therefore under capacity by 42 to 79 %. Table 7.8 provides the specific detail of the relationship. Given the under-capacity of cross sections 26 and 31 to an event of the 1995 magnitude, and assuming no modification of the channel in Reach 4, the flow in such channels would be significantly overbank. Therefore some flow is likely to be carried by the lower Reach 3 channel, which would increase the likelihood of the destruction of the left bank rip-rap. Given this scenario Table 7.8 also indicates the difference in capacity between the upper Reach 3 channel and the combination of lower Reach 3 and Reach 4 channels. Even under this scenario in most cases the 1995 flows could not be contained by the combination of channels alone.

These simple calculations show the inability of the newly engineered channels to cope with flow capacities experienced in the 1995 flood. The engineering has countered the natural hydraulic behaviour, which would be to allow flow to disperse at the fan apex, thereby reducing the capacity and competence of the flow (Blair and MacPherson, 1994), and reducing the likelihood of downstream flooding and sedimentation. This situation poses questions with regard to future flooding, which are now considered.

Figure 7.17: Maximum calculated channel capacities in the Raise Beck catchment relative to altitude and distance.

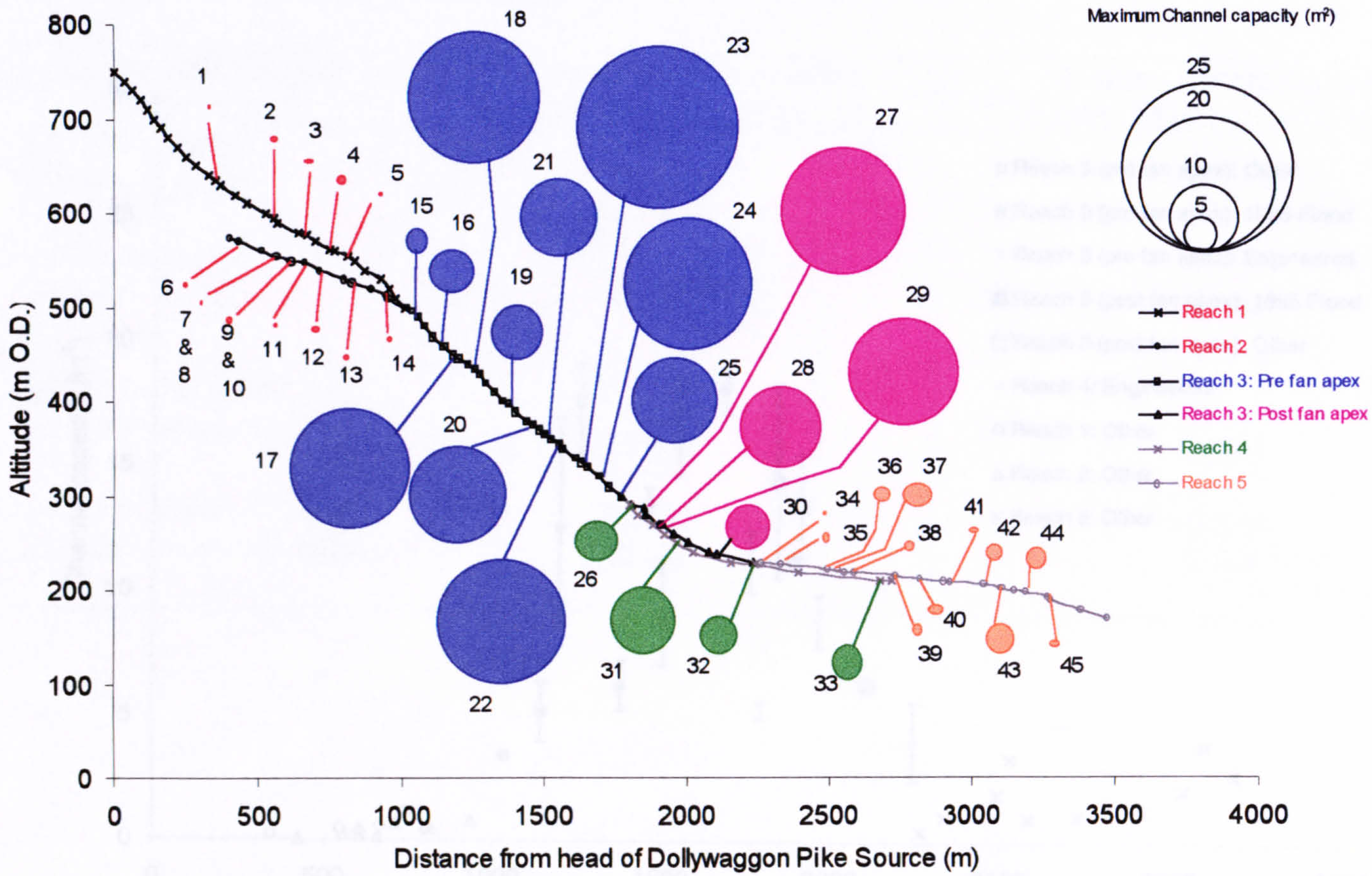


Figure 7.18: The range of Raise Beck channel capacities, relative to distance. Values with vertical bars are mean capacities with associated maximum and minimum values. Other capacities are from basic width/ depth measurements, and are the approximate maximum values (Reach 1,2, & 5)

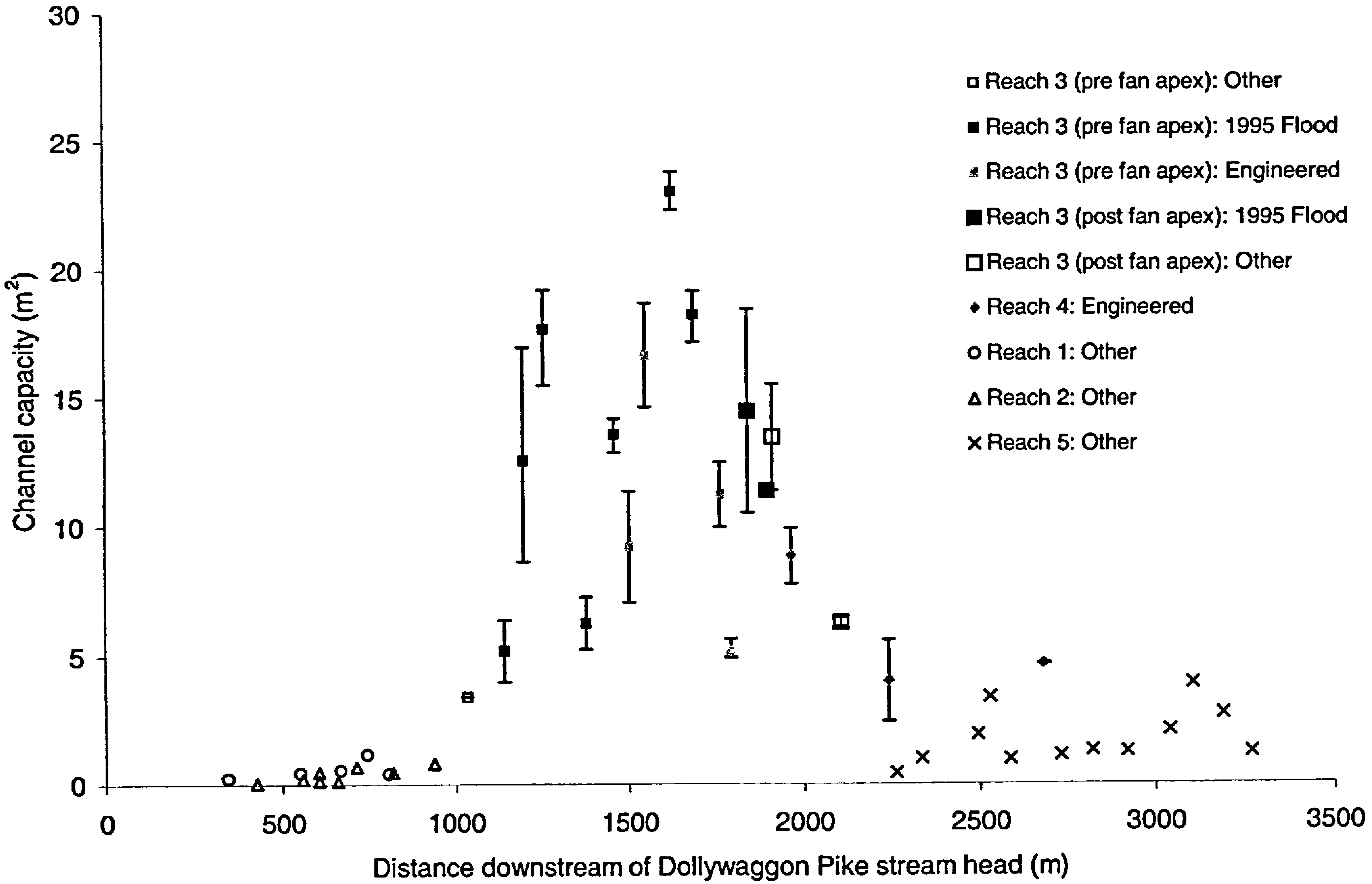


Table 7.8: Percentage size difference of individual and combined fan apex cross sections (xs), relative to the range of 1995 flood capacities calculations reconstructed in sections 23 and 24 above the fan apex. (Negative values show undersizing, and positive values show capacity in excess of requirement.)

Cross-section and capacity (m^3)	% size difference relative to max. capacity of xs. 23	% size difference relative to min. 1995 capacity of xs. 24
26 (Max- 5.692)	-74.97	-65.29
26 (Min- 4.935)	-79.28	-71.27
31 (Max- 9.953)	-58.21	-42.06
31 (Min- 7.786)	-67.31	-54.68
26 + 27 (ΣMax- 21.144)	-11.227	+23.081
26 + 27 (ΣMin- 15.474)	-35.032	-9.925
26 + 28 (ΣMax-17.239)	-27.622	+0.349
26 + 28 (ΣMin- 16.194)	-32.09	-5.734

7.5.8 Future flooding

In the absence of flow gauging at Raise Beck or similar mountainous catchments nearby, the best surrogate for event magnitude and frequency is that provided by the palaeo-channel deposits and rainfall records. The rainfall causing the 1995 flood was statistically a 1 in 80 year event (Sanders, 1995). The events which produced flood units 1 and 2 were probably of greater magnitude and therefore likely to occur less frequently than 1 in 80 years, assuming that rainfall and flood frequencies broadly correspond. The records of Kelbarrow (1898), and Huddleston (1935) indicate that geomorphologically effective floods have occurred at Raise Beck more than once in an eighty-year period. However, this is not to say these floods were of the same magnitude as the 1995 flood.

Climate change scenarios for northern Britain all suggest a tendency towards increased precipitation and a rise in temperature. These changes translate into a general increase in river flows in upland Britain, especially in the winter months (Arnell, 1999). Therefore the flood risk is likely to increase and the recurrence interval for a flood with the 1995 event magnitude would reduce, i.e. become a more frequent occurrence.

No design flood was specified in the engineering reconstructions following the 1995 event. Instead the contractor was left to his own devices (Rycroft, 1998, 2000). Given this arbitrary approach, and the absence of stream gauging it is not possible to define the design limit of the engineered channels, other than to say it is less than the 1995 flood event, based on the previous calculations of the reduced capacity of the channels beneath the fan apex. The adequacy of this flood defence will ultimately be determined by North West Water and the National Trust, who are the landowners and managers of the catchment, along with Cumbria County Council, who will be responsible for any cost incurred in the repair of Raise Beck, the road and other impacts if the engineered channel is breached and destroyed by a future flood. To determine the acceptability of the level of defence these agencies should consider whether the level of investment and design strategy employed in containing Raise Beck is sufficient to outlay the costs of future flooding.

Channelising Raise Beck to the north will contain low and moderate flows, preventing any flooding and sedimentation of the A591 at Dunmail Raise. However, in significant floods the road is still likely to be affected by water and sediment as the engineered channel will be breached. Alternatively, allowing water to disperse across the fan would only offer similar low levels of defence. Such a strategy would have implications for water supply to Thirlmere reservoir, the lack of control over the waters path on the fan surface and would require the cleaning and enlargement of the culvert under the A591 to prevent blockage. The most appropriate solution would be an enlargement of the current right bank channel so it provides greater levels of flood defence. Further active mitigation measures such as sediment check dams as applied elsewhere in the world to mountain torrents (Eisbacher and Clague, 1984; Thurber, 1984; VanDine, 1985, Kellerhals and Church, 1990; Lewin and Warburton, 1994; Jaeggi and Pellandini, 1997) would enhance the flood protection, but at a financial and environmental cost. Additionally stream gauging of Raise Beck would improve the understanding of this system and therefore provide information on the appropriateness of any engineering scheme.

7.6 Conclusion

This study using geomorphological, sedimentological, hydrological and documentary evidence has demonstrated that the adjustment of the channel morphology at Raise Beck is governed by high frequency - low magnitude flood events. Over approximately the last 150 years the evidence of up to three large floods are preserved in the Raise Beck catchment, these being the 1995 flood and two floods in the mid Nineteenth Century. Other floods have occurred, but evidence of these is more limited. The three formative floods are likely to equal and exceed a recurrence interval associated with a 1 in 80 year rainfall event, though this is only a first approximation, as Houghton-Carr (1999) reminds us that inferences about flood rarity based on rainfall statistics must remain tentative.

A comparison of palaeohydrological and rainfall-runoff methods for estimating the discharge of the 1995 event generally illustrates that discharge values obtained with the palaeohydrological methods were an order of magnitude greater than those obtained with the rainfall-runoff methods. This overestimation of discharge probably reflects inaccuracies in the calculation of both velocity and channel capacity. The equations used to calculate velocity fail to consider the effect of very steep channel gradients, which Clarke (1996) states would lower the velocity required to transport boulders. Bank collapses in the turf scour line will over estimate the flood stage in some cross sections. Therefore, taking the rainfall-runoff values to be more realistic, the assertion of Costa (1983) that palaeohydraulic equations like those he reports can *"produce discharge estimates of past flood peaks that are far more accurate than order of magnitude estimates"* may be questionable in this type of catchment.

The engineering of Raise Beck following the January 1995 flood has provided a short-term management solution to the problem of flooding in this torrent catchment. The management strategy would fail to contain the discharge of an event identical to that occurring in 1995, and with predicted climatic changes for northern Britain it is anticipated that large flood discharges will occur more frequently. Therefore overbank flooding of Raise Beck, and possible damage and disturbance of the A591, will become a more frequent occurrence. To alleviate this, it suggested that the right bank channel be enlarged, and that active mitigation measures be installed to halt the transport of large boulders.

More generally this study has shown the need for detailed monitoring of steep upland rivers and torrents, most especially their stage-discharge relationships. This information would allow more appropriate levels of flood defence to be applied to steep upland streams that pose a hazard to upland communities and infrastructure as in the case of Raise Beck. The installation of a weir at Raise Beck would currently help little in the design of enlarged channels, but would in the future provide a valuable record by which to accurately assess the controls on flood events in these steep torrent catchments.

CHAPTER 8: REGIONAL ASSESSMENT OF SEDIMENT-WATER FLOW ACTIVITY IN THE LAKE DISTRICT

8.0 Scope of chapter

This chapter presents the results of the regional reconnaissance of torrents and debris flows in the Skiddaw and Helvellyn massifs, in the northern and central Lake District respectively. The aim of the investigation is to establish the significance and the siting characteristics of these features. First, the background (section 8.1) to this investigation and other similar studies in mountainous areas is given. Investigations of the Swiss floods and debris flows of summer 1987 provide a good example of the type of approach used to identify and measure process activity at a regional scale. Section 8.3 outlines the methodology used in this investigation of torrents and debris flows. Section 8.4 considers the importance of torrents and debris flows in the study area (section 8.4.1), the morphology of sites (section 8.4.2), the local geology (section 8.4.3), and the magnitude and frequency of torrent and debris flow events (reconstructions of flow dynamics and age) (section 8.4.4). The context of the Iron Crag and Raise Beck torrents, within the overall 250 km^2 study region is considered (section 8.4.5). Finally, section 8.5 concludes the survey and draws attention to extensions of study.

8.1 Background

8.1.1 Lake District regional investigation

This chapter provides a broader context of torrent and debris flow activity in Lake District mountain catchments. The areas investigated are the Helvellyn and Skiddaw mountain massifs, which contain Raise Beck and Iron Crag respectively. The main reasons for selecting these two areas are their easily defined geographical boundaries and the contrasting geology of the two massifs. The definition of each region is generally given in Lake District National Park Authority management plans of each massif (LDNPA, 1997a; LDNPA, 1997b). These are areas of sustained higher relief, whose lower boundaries are defined by roads and tracks at lower altitudes in valley bottoms (Figure 3.11).

8.1.2 Examples of regional studies of mountainous process activity

A number of published studies consider debris flow and torrent activity at the regional scale. These include:

1) Campbell (1974, 1975)- debris flows and soil slips in the Santa Monica Mountains following a heavy rainstorm in January, 1969.
2) Innes (1983a, 1989)- the distribution of debris flows in Scotland using aerial photography.
3) Lister *et al.* (1984) and Lister and Morgan (1989) investigate debris torrents (channelised debris flows, in torrent channels) along Howe Sound, British Columbia.
4) Rickenmann and Zimmermann (1993) summarise aspects of a detailed Swiss Government investigation into the floods and debris flows that occurred in the 1987 in the Swiss Alps.

The Swiss investigation is considered in more detail as this provides a methodological approach that can be applied to the Lake District regional investigations.

In Switzerland in the summer of 1987 a large number of floods and debris flows occurred following two intense rainstorms, July 18-19th and August 24-25th (Rickenmann and Zimmerman, 1993). These centered on three high mountain areas, namely the Vorderrhein/ Blenio valleys; the Puschlav; and Gotthard region. Many of these events impacted on inhabited areas and caused extensive damage to torrents and their fans. They affected areas of different geological formation and land use, and amounts of rainfall varied. The Swiss Federal Government commissioned a Federal research program to investigate this problem (Petrascheck, 1990). This program had five goals (Haeberli *et al.*, 1990): 1) indicate the distribution of events in severely affected regions, 2) reconstruct the dynamic behaviour of the most spectacular events, 3) analyse variables which led to debris flows, 4) use the collected data to test and/ or create empirical rules for hazard prediction, 5) outline long-term trends and developments in view of past climate and predicted atmospheric warming.

Zimmermann (1990) and Rickenmann and Zimmermann (1994) describe results considering the first three goals. The distribution of features was mapped using vertical and oblique aerial photographs taken shortly after the events. These were used to locate undisturbed debris flows in remote regions of the three main areas. The location of some 600 debris flows were marked on topographic maps. Basic flow parameters were derived from the photographs, i.e. starting zone altitude, flow length, deposition characteristics and debris flow volume. More detailed geomorphological investigations were undertaken on the largest of the debris flows which affected human settlement. Detailed field mapping along the flow path, combined with eyewitness observations, historical records, ground and aerial photographs prior to and after the 1987 events, collectively allowed reconstruction of individual events. The chronology of events, source of material, and the velocity and discharge of flow were calculated. The third objective, considering variables leading to debris flows and their characteristics, was undertaken using data derived from the previous two approaches, i.e. analysis of aerial photographs plus data from the reconstruction of larger events. Relationships between morphometric characteristics (slope of starting zone and catchment area, maximum erosion depth and bed slope, mean sediment yield and fan slope) were analysed.

This Swiss investigation shows that aerial photography provides an efficient means of identifying sites and obtaining basic measurements of debris flows and torrents across large areas. Once sites are identified further information can be gained from field surveys, consulting local records for historical activity and witnesses for details of recent events. However, neither Zimmerman (1990) and Rickenmann and Zimmermann (1994) state in detail how field measurements were made and recorded.

A useful approach for conducting similar measurements at many different locations is using pro-forma check sheets. Kienholz *et al.* (1984) and Zimmerman *et al.* (1986) outline check sheets designed to assess mountain hazards in Nepal. Similarly, Thorne (1991, 1998), and Thorne and Easton (1994) advocate check sheets for river reconnaissance. Thorne and Easton (1994) state that such sheets provide the basis for repeatable observation and interpretation, and provide an *aide memoire* for field personnel. They also note that pro-forma check sheets need to be tailored to the requirements of a particular study, hence none of the previous proformas were applicable to the study of torrents and debris flows in the Lake District. Nevertheless the method is of general utility providing a useful approach for conducting geomorphological field reconnaissance and measurement.

8.2 Aims and objectives

The aim of this investigation was to undertake an assessment of sediment- water flow activity in two Lake District mountain massifs and provide a context to the detailed investigations undertaken at Iron Crag and Raise Beck. This includes five specific objectives:

1) Evaluate the overall significance of torrents and debris flows in the Skiddaw and Helvellyn mountain massifs.
2) Using morphometric indices, determine whether there are preferred site characteristics for torrents and debris flows.
3) Establish whether there are significant differences in the torrents and debris flows in the two massifs of contrasting geology.
4) Assess the magnitude and frequency characteristics of torrent and debris flow systems.
5) Compare Iron Crag and Raise Beck to other sites in the region.

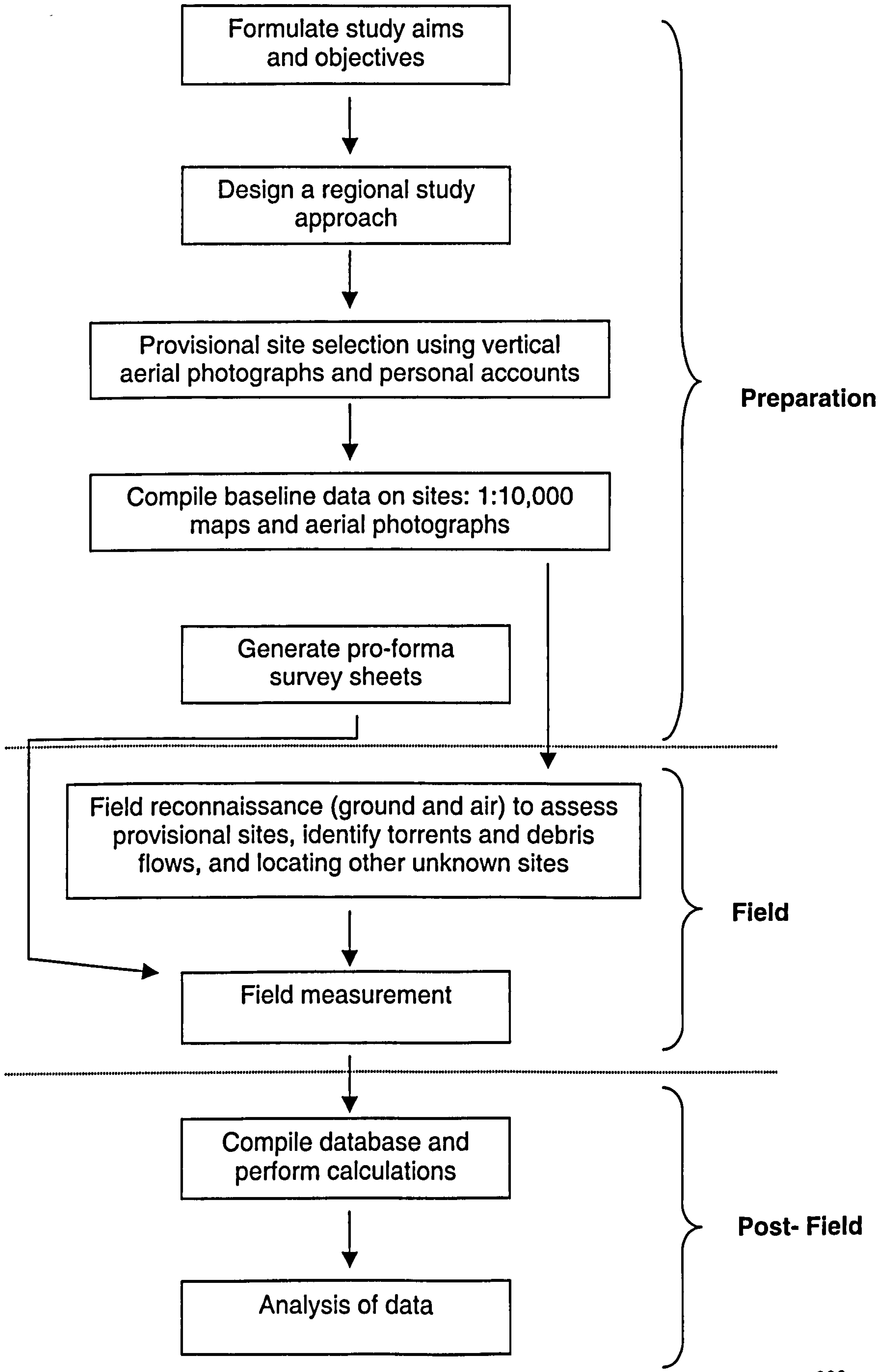
8.3 Methodology

The methodology applied in this regional investigation is summarised by Figure 8.1. The investigation was composed of three main phases: field preparation; field reconnaissance and survey; and analysis of the results. Each of these phases is now described in more detail.

8.3.1 Pre-field phase

The investigation draws heavily on the approach outlined by Rickenmann and Zimmermann (1994) (section 8.1). The location of potential torrents and hillslope debris flows were determined from colour vertical aerial photographs held by the

Figure 8.1: Approach applied to the study of torrents and debris flows across the Skiddaw and Helvellyn massifs.



Lake District National Park Authority at Kendal. The aerial photographs were taken in 1988 under the copyright of ADAS at a scale of 1: 18,000. Additional sites were suggested by eyewitness accounts and field observation. For example, hillslope debris flows were reported by the Cumbria RIGS group at Clough Head (NY 334 228). Aerial photographs and corresponding extracts of 1: 10,000 maps provide the baseline information for the field reconnaissance. The location of all sites and their means of identification are shown by Figures 8.2 and 8.3. In these figures a unique number identifies each site, the count starts in the Skiddaw massif (Figure 8.2) and then moves onto the Helvellyn massif (Figure 8.3). Later identification of sites in the field (ground and air) result in the addition of numbers to an otherwise systematic sequence. During the reconnaissance phase 65 sites are considered, 23 on the Skiddaw massif, and 42 on the Helvellyn massif.

Prior to field investigations proformas for both torrents and debris flows were prepared (Appendix 8.1). Common to both is an initial cover sheet which records basic site details, makes an assessment of risk features, human interference, geomorphological setting, drainage and vegetation. In addition, torrents have four specific sheets considering fluvial palaeohydrology, channelised debris flow reconstruction, hillslope sediment sources, and finally a sheet for the basal fan characteristics. Debris flows have three sheets covering the starting zone, the flow track/ levee zone, and the depositional toe area. The information listed on these sheets cover basic morphometric criteria and specific measurements required for the reconstruction of velocity and discharge. These criteria were obtained from literature on both fluvial reconstruction (e.g. Costa 1983; Williams and Costa, 1988) and debris flow reconstruction (e.g. Johnson and Rodine, 1984; Steijn *et al.*,1988). A final proforma, common to both features was a stratigraphic log derived from the sedimentological literature (e.g. Friedman and Sanders, 1978; Briggs, 1981; Davis, 1992).

Figure 8.2: All sites considered at the reconnaissance phase of fieldwork on the Skiddaw Massif

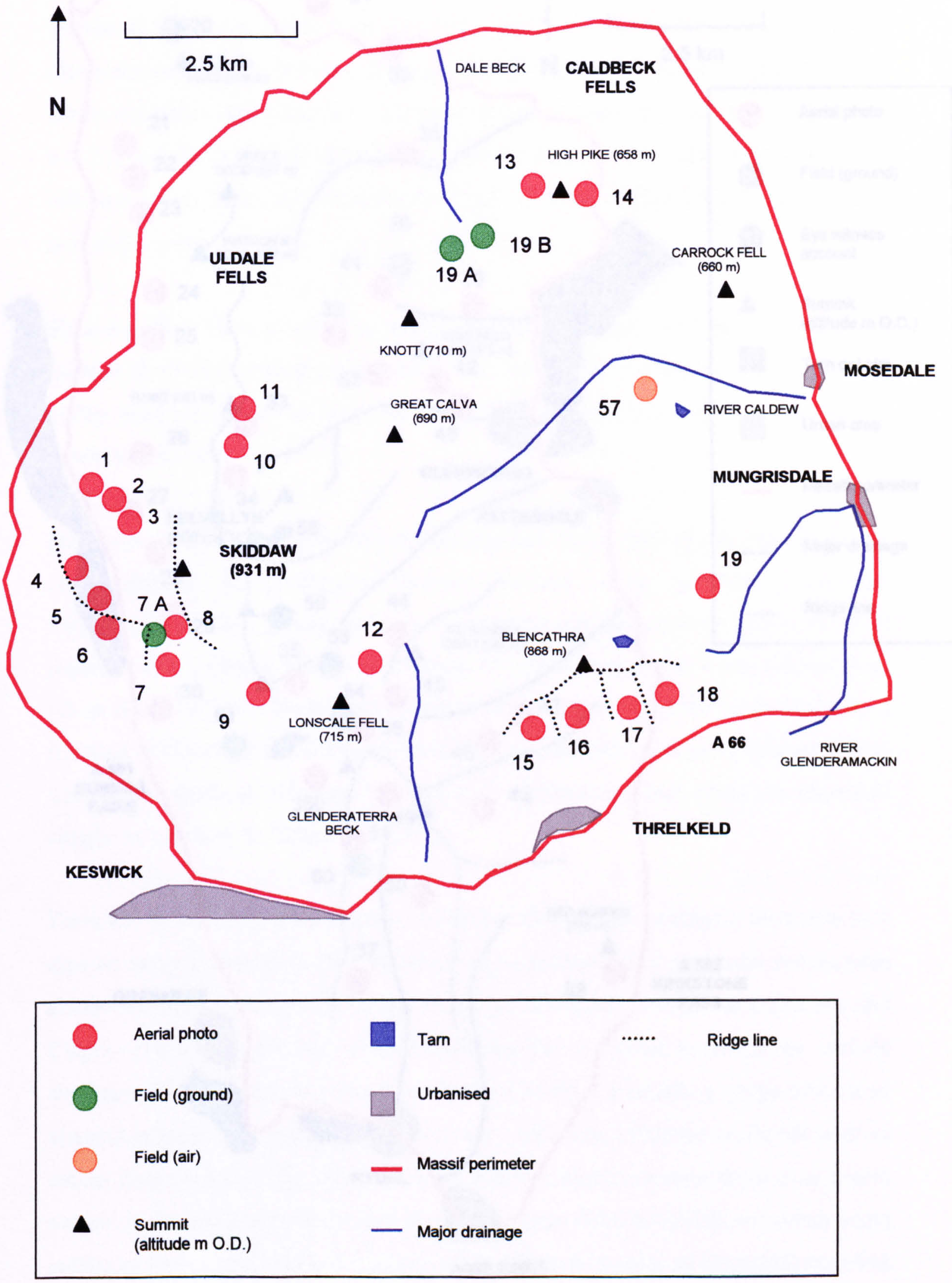
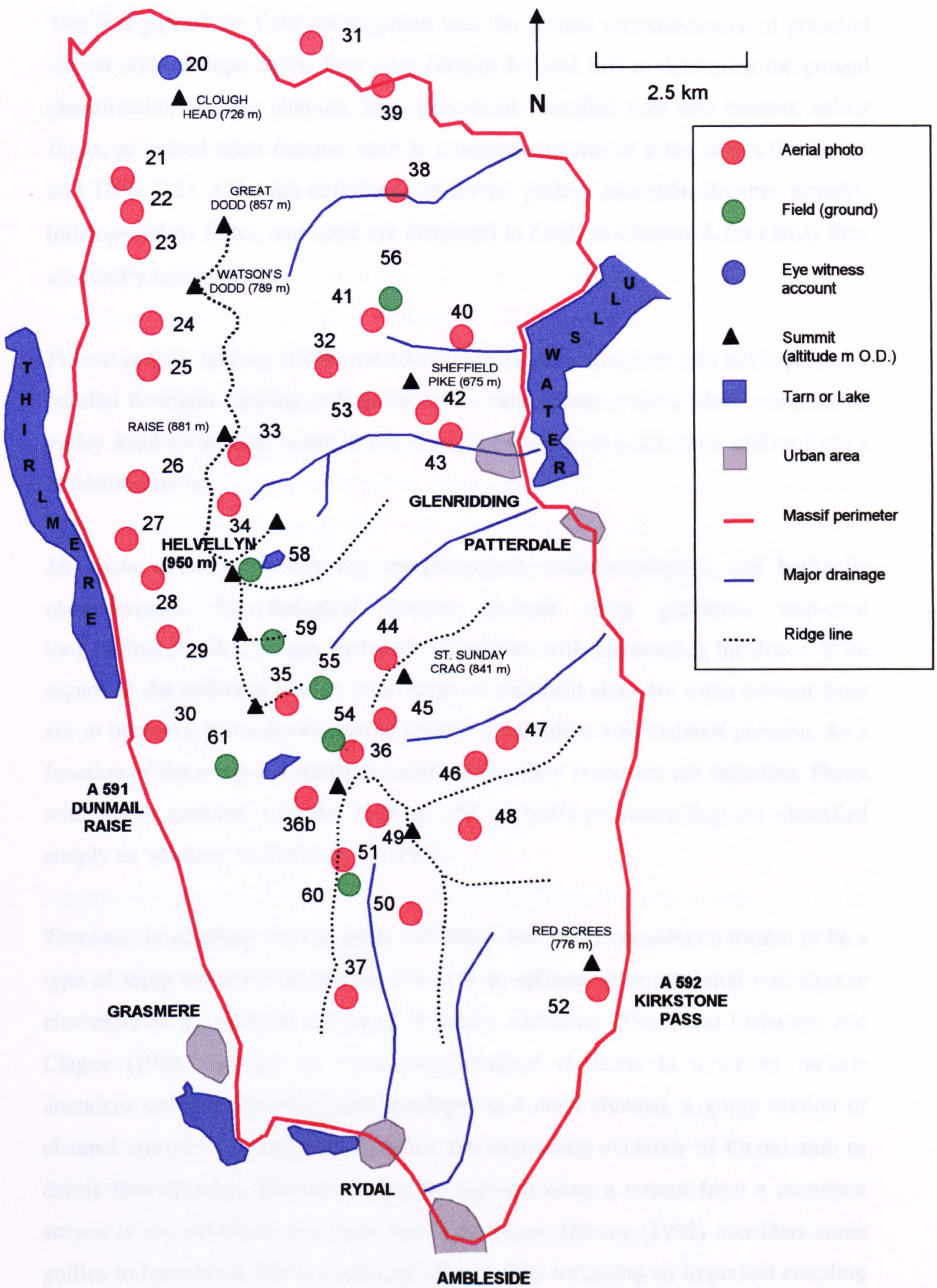


Figure 8.3: All sites considered at the reconnaissance phase of fieldwork on the Helvellyn Massif



8.3.2 Field investigations

The first part of the field investigation was the ground reconnaissance of potential torrent and hillslope debris flow sites (Figure 8.2 and 8.3) to determine the ground classification of these features. This assessment classified sites into torrents, debris flows, or indeed other features such as mountain streams or scree slopes (Table 8.1 and Table 8.2). Although definitions of fluvial gullies, mountain streams, torrents, hillslope debris flows, and scree are discussed in detail in Chapter 2, for clarity they are briefly reiterated here.

Fluvial gullies: Harvey (1996) considers these as linear incisions into hillslopes, with parallel flowlines running orthogonal to the valley floor system. More complicated valley head forms also occur in the Howgill Fells where convergent gullies form a dendritic network.

Mountain streams: possess key morphological, sedimentological, and hydraulic characteristics. Morphological features include steep gradients, step-pool longitudinal profiles, gorges, and some interaction with surrounding hillslopes. With regard to the sediment load, a wide range of sediment sizes are often evident from silt to boulders, but a dominance of cobble and boulder size material prevails. As a function of the steep and irregular environment, flow processes are turbulent. Flows with lower gradient, minimal bedload and no hillslope interaction are classified simply as 'streams' in Tables 8.1 and 8.2.

Torrents: In adopting the European definition, this study considers a torrent to be a type of steep mountain catchment, which is an ephemeral or perennial watercourse characterised by sporadic discharge of debris. Eisbacher (1982) and Eisbacher and Clague (1984) suggest the main morphological elements in a torrent include abundant sediment delivery from hillslopes and main channel, a gorge section or channel constriction, and a basal debris fan expressing evidence of fluvial and/ or debris flow activity. The critical feature distinguishing a torrent from a mountain stream is the existence of a basal fan in a torrent. Harvey (1992) considers some gullies to have basal debris cones and alluvial fans reflecting an imperfect coupling between the hillslope and basal channel system. However, these gullies are smaller, and have simpler morphology than exhibited by torrents.

Debris flows: Costa (1988) considers these to be characterised by both sedimentological and geomorphic criteria. Sedimentological features include matrix supported material, no imbrication, no stratification, and inverse grading (Costa, 1988; Scott *et al.*, 1995). The morphological evidence for debris flows includes lateral levees and lobes (Wells and Harvey, 1987; Costa, 1988) with the sedimentological structures outlined, and possibly deeply incised channels (Coussot and Meunier, 1996). Following Takahashi (1981) debris flows can be categorised according to their starting zones, i.e. hillslope or channel based. Both forms are considered in this investigation, though evidence of debris flow activity in channels rarely persists as fluvial activity destroys levees and lobes. In contrast, hillslope debris flows may remain undisturbed and revegetation preserves the characteristic ridge and furrow pattern of the flow track and levees. Such features are considered as palaeo forms, and are distinguished from current hillslope debris flow deposits that exhibit little or no revegetation.

Scree: Ballantyne and Harris (1994) state that scree generally refers to any slope cover of coarse debris irrespective of location, and distinguish this from talus. These scree slopes are often areas of loose and unvegetated debris exhibiting a downslope sorting according to clast size.

Ground reconnaissance identified the main torrent and debris flow sites considered for further analysis. Figures 8.4 and 8.5 show the sites where detailed field measurements were made. Included in these are additional sites located during the field reconnaissance which were not initially identified on the aerial photographs. These features were either too small to be seen on the aerial photographs or were formed after 1988 when the photographs were taken. Following the ground-based reconnaissance, flights over the two massifs (Skiddaw- October 1999; Helvellyn- May 2000) confirmed the classification of the features identified and the existence of only one previously unidentified debris flow deposit. Field measurements and observations were performed using baseline maps, aerial photographs, and proforma check sheets.

Table 8.1: The classification of all potential sites following field reconnaissance

Massif	Site Number	Site Name	Classification
SKIDDAW (23 sites)	1	White Hoarse	Scree/ slate mine
	2	Barkbethdale Gill	Scree
	3	South Barkbethdale	Torrent
	4	Ullock Pike	Palaeo hillslope debris flows
	5	Ullock Pike channel	Scree
	6	Gable Gill	Scree/ mountain stream
	7	Slades Beck	Mountain stream
	7a	Carlside	Channelised debris flow
	8	Tongues Beck	Torrent
	9	Howgill Tongue	Scree/ mountain stream
	10	Dead Crags	Scree
	11	Foul Gill	Torrent
	12	Lonscale Fell	Scree
	13	Birk Moss	Mine workings
	14	Dry Gill	Fluvial gully
	15	Blease Gill	Mountain stream
	16	Gate Gill	Mountain stream
	17	Doddick Gill	Mountain stream
	18	Scaley Beck	Mountain stream
	19	Bannerdale Crags	Torrent
	19a	Iron Crag west	Fluvial gully
	19b	**IRON CRAG**	Torrent/ channelised debris flow
	57	Bowscale Tarn	Hillslope debris flow
HELVELLYN (42 sites)	20	Clough Head	Hillslope debris flows
	21	Beckthorns Gill	Mountain stream
	22	Fornside	Stream
	23	Mill Gill	Mountain stream
	24	Stanah Gill	Mountain stream
	25	Sticks Gill/ Fisherplace Gill	Mountain stream
	26	Helvellyn Gill	Mountain stream
	27	Dry Gill	Mountain stream
	28	Brownrigg Well	Mountain stream
	29	Whelpside	Mountain stream
	30	Birkside Gill	Mountain stream
	31	Mosedale Beck	Mountain stream
	32	Greenside	Hillslope debris flow
	33	Keppel Cove	Scree
	34	Brown Cove	Hillslope debris flows
	35	Cook Cove	Scree
	36	Deepdale Hause south	Scree
	36b	Fairfield Brow	Torrent/ hillslope debris flow
	37	Blind Cove	Fluvial gully
	38	Rush Gill	Mountain stream
	39	Sandbedmoss	Fluvial gully
	40	Glencoyne Beck	Mountain stream
	41	Scot Crag	Scree
	42	Glenridding Screes	Scree
	43	Glenridding Beck	Mountain stream
	44	St. Sunday Crag	Scree
	45	Bannerside	Scree
	46	Hartsop above How	Stream
	47	Hoggill Brow	Stream
	48	Hoggett Gill	Torrent
	49	Rydal head	Scree
	50	Dale Head Close	Stream
	51	Great Rigg	Scree
	52	Red Screes	Scree
	53	Swart Beck	Mountain stream
	54	Deepdale Hause north	Hillslope debris flow
	55	Falcon Crag	Hillslope debris flow
	56	Wintergroove Gill	Torrent
	58	Striding Edge	Hillslope debris flow
	59	Nethermost Cove/ Ruthwaite Cove	Scree
	60	Rydal Fell	Torrent
	61	**RAISE BECK**	Torrent

Table 8.2: A summary of potential site classifications following field reconnaissance

Massif	Classification	Frequency
Skiddaw	Torrents	5
	Hillslope debris flows (current)	1
	Hillslope debris flows (palaeo)	1
	Channelised debris flow	2
	Mountain streams	7
	Fluvial gullies	2
	Scree slopes	7
Helvellyn	Torrents	5
	Hillslope debris flows (current)	7
	Mountain streams	14
	Streams	4
	Fluvial gullies	2
	Scree slopes	11

8.3.3 Analysis of field data

This principally involved compilation of field measurements, additional measurements from aerial photographs and maps, and the calculation of palaeo velocity and discharge. Tables 8.3 and 8.4 show the morphometric and event dynamics for torrents and debris flows. Additional information is also available on: particle size characteristics of source sediments and debris flow levees, source material volumes, site photography, and field mapping.

The equations used here for the calculation of velocity and discharge are:

Debris flow mean velocity (Johnson and Rodine, 1984; Steijn *et al.*, 1988):

$$V = (g\ r \cos\delta \tan\beta)^{1/2} \qquad \text{(Equation 8.1)}$$

Debris flow peak discharge (Steijn *et al.*, 1988):

$$Q = V\ \pi\ WD/4 \qquad \text{(Equation 8.2)}$$

Fluvial velocities from boulder size (Costa, 1983):

$$V = 0.18\ d_i^{\ 0.487} \qquad \text{(Equation 8.3)}$$

Figure 8.4 Torrents and debris flows on the Skiddaw Massif selected for measurement after field reconnaissance

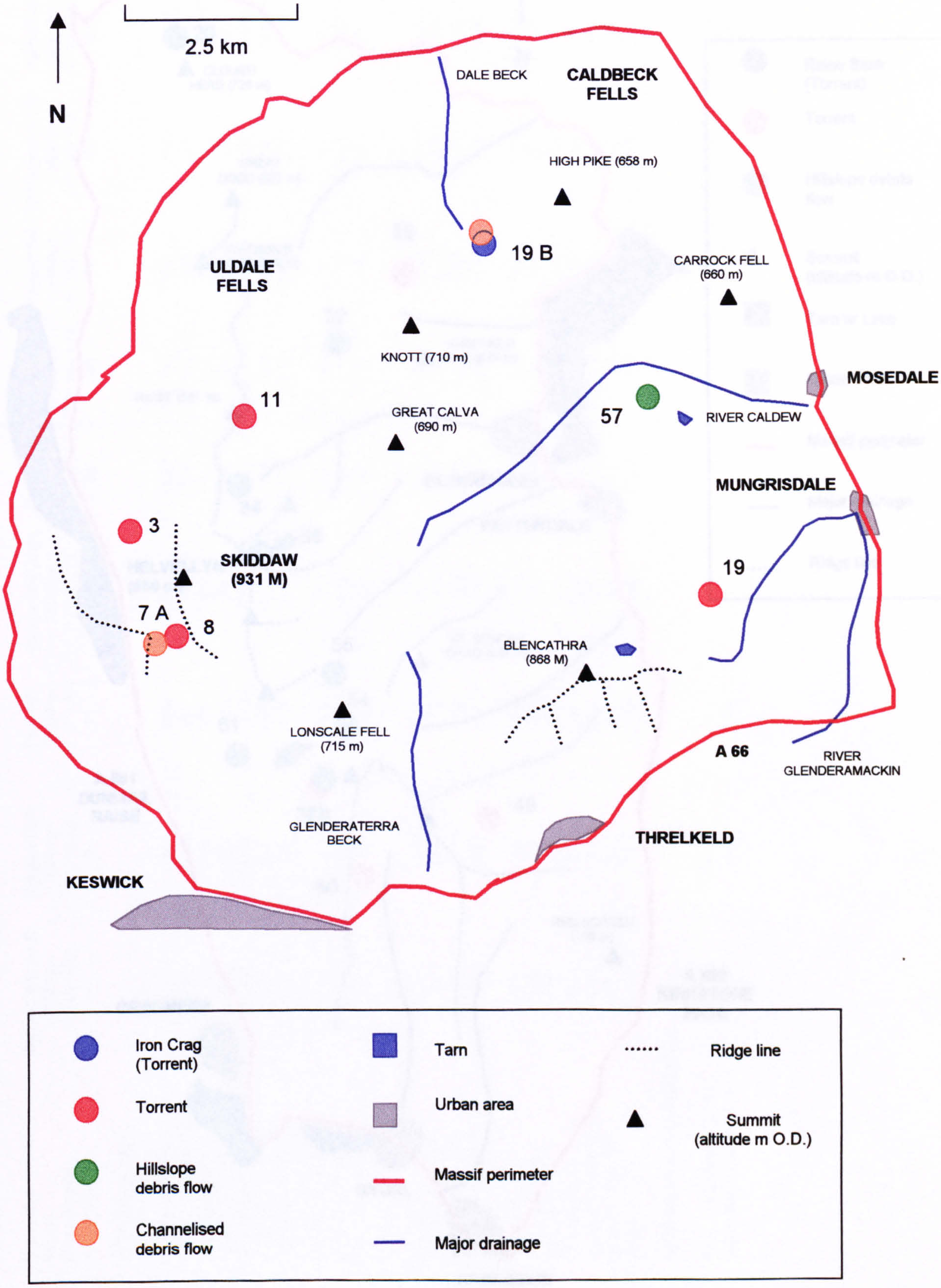


Figure 8.5: Torrents and debris flows on the Helvellyn massif selected for measurement after field reconnaissance

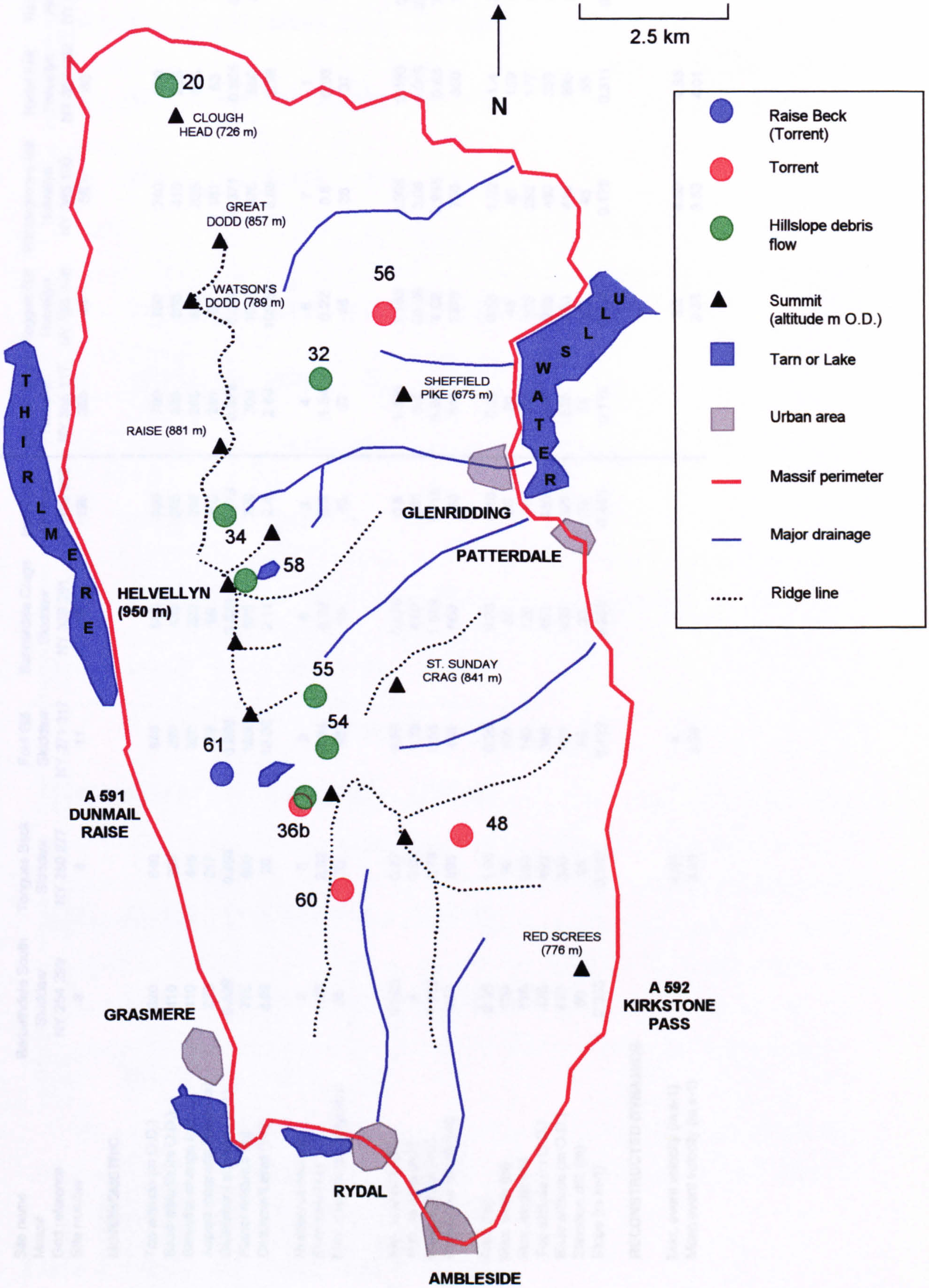


Table 8.3: Torrent measurements

	GENERAL										
	Site name	Barbethdale South	Tongues Beck	Foul Gill	Bannerdale Crags	Iron Crag	Fairfield Brow	Hoggett Gill	Wintergroove Gill	Rydal Fell	Raise Beck
	Massif	Skiddaw	Skiddaw	Skiddaw	Skiddaw	Skiddaw	Helvellyn	Helvellyn	Helvellyn	Helvellyn	Helvellyn
	Grid reference	NY 254 299	NY 260 277	NY 271 317	NY 339 291	NY 305 342	NY 355 117	NY 385 108	NY 365 190	NY 357 092	NY 330 119
	Site number	3	8	11	19	19b	36b	48	56	60	61
	MORPHOMETRIC										
System	Top altitude (m O.D.)	820	840	640	655	600	790	780	740	600	858
	Base altitude (m O.D.)	410	395	290	435	395	525	230	415	295	235
	Elevation change (m)	410	445	350	220	205	265	550	325	305	623
	Aspect magnetic (degrees)	273	217	259	96	350	251	65	181	63	261
	Catchment slope (m m-1)	0.529	0.494	0.280	0.326	0.273	0.379	0.338	0.371	0.555	0.249
	Planar distance (m)	775	900	1250	675	750	700	1625	875	550	2500
	Catchment area (ha)	3.92	26	13.08	2.11	2.4	2.66	105.58	6.65	2.96	133
Slopes	Number of sources	2	3	9	6	3	4	6	7	1	4
	Sum area (ha)	1.33	2.92	0.84	0.29	0.3	1.64	0.22	0.8	0.03	0.07
	Max. slope angle (degrees)	35	32	45	40	45	37	48	38	37	-
Channel	Min. xs area (m2)	0.325	0.77	0.66	0.575	0.8	1.125	1.155	0.385	0.193	0.045
	Max. xs area (m2)	4	6.93	1.75	4.02	2.61	5.4	10.78	3.08	1.348	23.818
	Mean xs area (m2)	1.465	1.79	0.95	1.639	1.715	3.841	4.62	0.935	0.63	7.257
	Active flow length (m)	462	596	445	600	490	615	1375	750	350	1750
Fan	Area (ha)	0.96	1.06	0.96	0.23	0.16	0.22	0.55	1.02	1.4	3.75
	Max. width (m)	120	92	155	20	58	20	45	80	159	250
	Max. length (m)	170	260	140	120	79	111	105	255	177	300
	Top altitude (m O.D.)	470	490	350	465	430	540	255	460	350	300
	Base altitude (m O.D.)	410	395	290	435	395	525	230	415	295	235
	Elevation diff. (m)	60	95	60	30	35	15	25	45	55	65
	Slope (m m-1)	0.353	0.365	0.429	0.250	0.443	0.135	0.238	0.176	0.311	0.217
	RECONSTRUCTED DYNAMICS										
	Max. event velocity (m s-1)		4.21	4				3.6	4.39	4.58	
	Mean event velocity (m s-1)		3.43	3.29				3.33	3.53	4.01	

Table 8.4: Debris flow measurements

	GENERAL																	
	Site name	Bowscale Tarn	Iron Crag Nov 99	Iron Crag Oct 00		Carlside		Clough Head 1	Clough Head 2	Clough Head 3	Greenside	Brown Cove 1	Brown Cove 2		Fairfield Brow	Deepdale Hause	Falcon Crag	Striding Edge
	Massif	Skiddaw	Skiddaw	Skiddaw		Skiddaw		Helvellyn	Helvellyn	Helvellyn	Helvellyn	Helvellyn	Helvellyn		Helvellyn	Helvellyn	Helvellyn	Helvellyn
	Grid reference	NY 332 321	NY 305 342	NY 305 342		NY 256 282		NY 334 230	NY 333 230	NY 333 229	NY 352 184	NY 343 162	NY 341 158		NY 353 116	NY 360 125	NY 352 129	NY 346 150
	Site number	57	19b	19b		7a		20	20	20	32	34	34		36b	54	55	58
	MORPHOMETRIC																	
System	Top altitude source (m O.D.)	460	570	570		720		575	655	550	635	745	825		700	680	570	840
	Base altitude (m O D.)	380	470	450		490		445	445	465	600	650	670		690	605	510	780
	Elevation change (m)	80	100	120		230		130	210	85	35	95	155		10	75	60	60
	Aspect magnetic (degrees)	5	350	350		165		312	299	325	150	119	73		-	308	111	49
	Catchment slope (m m-1)	0.58	0 40	0 40		0.46		0 565	0.553	0 500	0.700	0 633	0 517		-	0.625	0.86	0 60
	Planar distance (m)	138	250	300		500		230	380	170	50	150	300		-	120	70	100
Slopes	Number of head sources	3	2	2		2		2	2	0	1	2	1		1	1	1	1
	Sum area (ha)	0.060	0 251	0.251		0.02		0.03	0.36	-	0.006	0 11	0.11		-	0.003	0.013	0 0462
	Max. slope angle (degrees)	40	45	45		32		41	37	-	34	35	36		37	34	34	38
DF flow track	Top altitude track (m O.D.)	415	570	570		680		535	575	535	-	670	800		700	675	565	820
	Base altitude track (m O.D.)	405	470	450		550		510	525	510	-	650	690		690	620	550	780
	Top altitude levee (m O D.)	407	545	545		655		510	495	510	630	670	780		700	660	565	820
	Base altitude levee (m O.D.)	390	470	450		550		445	445	465	600	650	670		690	615	510	780
	Length levee (slope distance, m)	54	187	227		235		154	149	176	72	45	149		18.5	87.5	78	74
DF extras	Channel depth (m)	-	0.49	0.935	0.535	0.45	0.43	0 305	-	-	-	37	0.6	0 54	-	0.44	0 68	-
	Erosion depth (m)	-	?, but was erosive	?	?	0.21	0	0	-	-	-	-	35	0	0	0.2	0.16	-
	Slope angle inner (mean, degrees)	33.5	67.5	42.5	38.5	33.5	24.5	25	-	-	-	27 5	17.5	21.25	35	45	24	-
	Slope angle outer (mean, degrees)	30	20	-	7.5	16	27	12.5	-	-	-	35	17.5	25	30	25	21 25	-
	RECONSTRUCTED DYNAMICS																	
				L 9-10	L 9-11	615 m	560 m						BC 2 upper	BC 2 lower				
	Radius of curvature (m)	-	1.5	1.7	2 1	2.15	1.95	2 35	-	-	-	-	5.2	3 1	-	2	3 8	-
	Channel slope (degrees)	21	20	18	18	35	22	24	31	-	-	23	32	28	-	24	30	-
	Flow width (m)	3 2	1 65	2.35	2.2	2.45	2.35	2.4	3	-	-	2 4	5 4	3 45	1.4	2.6	4.2	-
	Superelevation angle (degrees)	-	12	9	4	3	2 5	4.5	-	-	-	-	4	3	-	5	4 5	-
	VELOCITY (m s-1)	-	1.714	1.585	1.17	0 951	0 879	1 287	-	-	-	-	1.739	1.186	-	1.25	1.594	-
	DISCHARGE (m3 s-1)		1.09	2 74	1.08	0.82	0 70	0.74					4.43	1.74		1.12	3.58	

In Equation 8.1 V = local mean velocity (m s^{-1}), g = gravitational acceleration (m s^{-2}), r = radius of curvature (m), δ = slope angle (degrees), β = angle of super-elevation between the inner and outer levees. Steijn *et al.* (1988) state that this calculation of velocity is based on the principle that the outer bend levee is higher than the inner levee due to the radial acceleration caused by curvature of the flow (Figure 8.6).

Equation 8.2 is reported by Steijn *et al.* (1988) to calculate the discharge for a semi-elliptical channel, which is considered to give a good approximation of debris flow tracks. The terms of the equation are: V = local mean velocity (m s^{-1}), W = width of debris flow (m), and D = depth of channel (m). Width (W) is the distance between the two levee tops, and channel depth (D) is the elevation difference between the top of the levee pairs and the lowest point of the channel incision. These and other terms are defined in Figure 8.6.

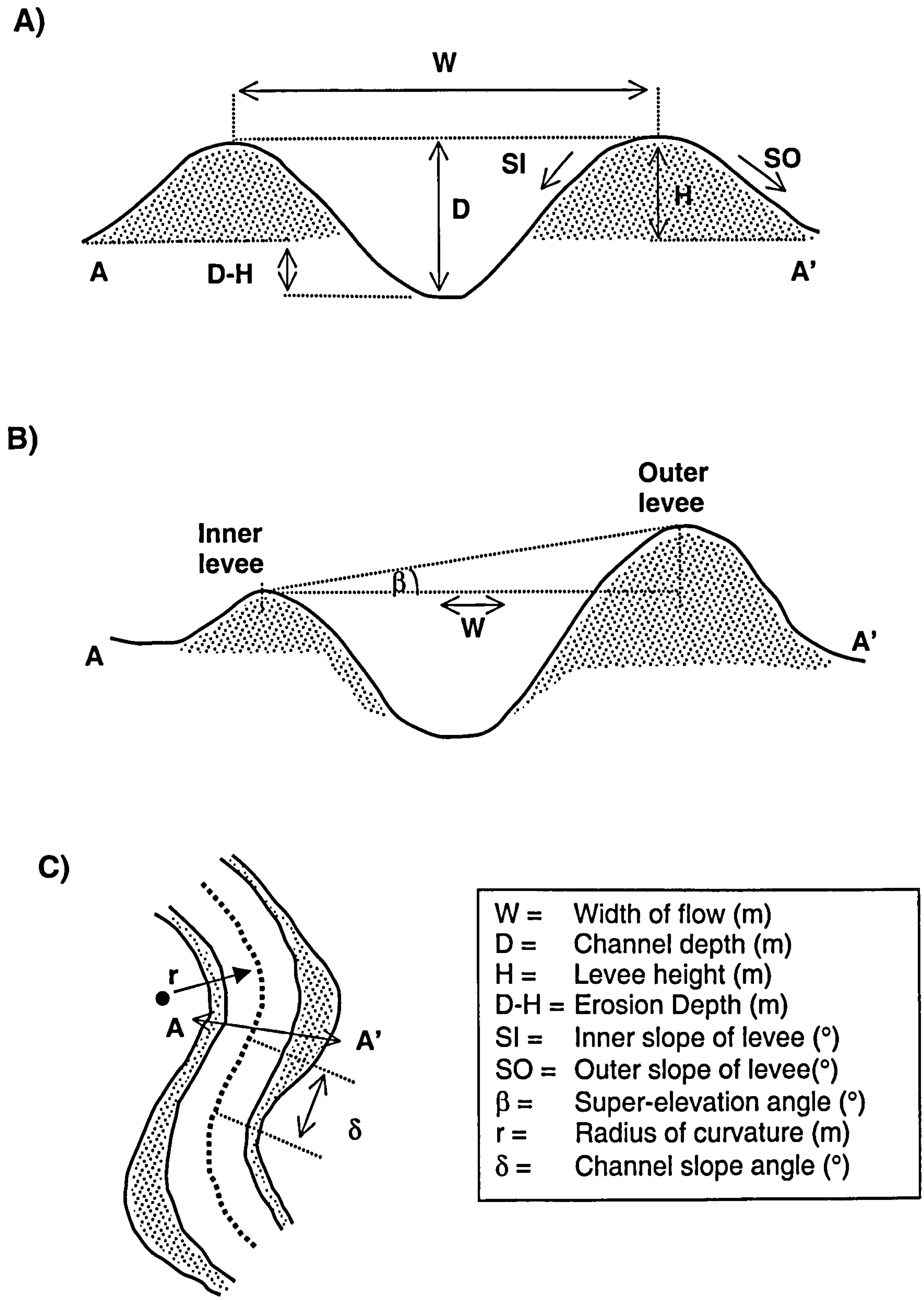
Equation 8.3 is identical to Equation 7.1; velocity is calculated from the mean size of the 5 largest boulders in a deposit, according to measurements of the b-axis (d_i). Further discussion of this equation is provided in Chapter 7.

8.3.4 Additional analyses

Objectives 1, 3 and 4 require additional information to that provided by the main aerial photography-field measurement programme. Objective 1 (the significance of torrents and debris flows in the study massifs) is investigated using an analysis of stream order of the drainage network as shown on 1:25,000 maps (blue lines). Included is the perennial drainage network (excluding mine leats) within the boundaries of the Skiddaw and Helvellyn massifs given in Figures 8.2 and 8.3. Stream orders are designated in accordance with Strahler (1957, p914) who states:

".. the smallest finger-tip tributaries are designated order 1. Where two first-order channels join, a channel segment of order 2 is formed; where two of order 2 join, a segment of order 3 is formed; and so forth."

Figure 8.6: Definition of debris flow levee morphometrical variables, including those used for the calculation of mean velocity and discharge. (A) Cross section with morphometric variables, (B) Super-elevated cross section, (C) Planform of paired levees (Adapted from Steijn *et al.*,1988)



As part of the analysis the stream network in each region was digitised and catchment areas, massif areas and stream order lengths calculated using Sigma Scan ™ measurement software.

Objective 3 (to establish whether significant differences in torrents and debris flows occur as a result of rock type) requires knowledge of the geology associated with each torrent and debris flow. The specific geology of these sites can be obtained from 1:50, 000 BGS sheet 29 (Keswick) and sheet 23 (Cockermouth), which show both solid and drift geology. However, in Section 8.4.3 generalised geological classes are applied, as the geological maps show many permutations of similar rock types, which would otherwise complicate this analysis. Furthermore, deposits of the drift geology include mixed lithologies that complicate the interpretation of local geological conditions.

Finally, Objective 4 considers magnitude and frequency aspects of torrents and debris flows. It assesses magnitude using the velocity calculations made previously, and uses lichenometry to date flood deposits in torrents (a measure of frequency). The lichenometric approach is identical to that used in Chapter 7, i.e. the mean size of the largest five lichens (mm) multiplied by a mean annual growth rate for *Rhizocarpon sp.* lichen. As with Raise Beck flood deposits, the growth rates of Macklin *et al.* (1992) and Merrett and Macklin (1999) are applied.

8.4 Analysis of regional sites

The following analysis addresses each objective in turn, using data from field measurements and subsequent map analyses (as outlined sections 8.3.3 and 8.3.4). With regard to objective 1, an assessment of the significance of hillslope debris flows cannot be performed using a stream order analysis, as they are not components of the drainage network, but instead slope features. Therefore objective 1 is only considered with regard to torrents. Approaches used in consideration of other objectives are largely applicable to both torrents and debris flows.

8.4.1 Overall significance of torrents and debris flows in the two massifs

An overall comparison of the drainage morphometry of each massif is outlined in Table 8.5. This shows the Helvellyn massif is slighter smaller in area than Skiddaw, but has a more extensive drainage network (41.93 km greater). This is reflected in the drainage density value for each, Helvellyn has a higher value of 2.6 km km^{-1}, relative to 2.1 km km^{-1} for Skiddaw. The results of the stream order analysis follow the expected trend with the first-order streams being greatest (in number and sum length), then declining for each successive order (Horton, 1945; Strahler, 1957; Zavoianu, 1985). Following Strahler (1957), a relationship between the logarithm of stream length and the logarithm of stream order (Figure 8.7), reveals a straight or near straight line fit between the plotted points. Helvellyn has a R^2 of 0.9779, whilst Skiddaw has an R^2 of 0.9361 for stream orders 1 to 4. Including the small length of 5^{th} order drainage in the Skiddaw massif reduces the R^2 of this relationship to 0.6481. However, this is not strictly valid as the drainage area of the 5^{th} order stream is truncated by the massif boundary.

Table 8.6 shows that all torrents originate as first order drainage features, though some of the larger torrents develop into higher order systems. In the case of Raise Beck and Hoggett Gill, third order segments are achieved. Thus, in most cases it appears that torrents are small-scale features in the headwater areas of catchments. First order streams account for the greatest cumulative length of streams in the massifs (Helvellyn 58 % and Skiddaw 49.5 %), but it does not necessarily follow

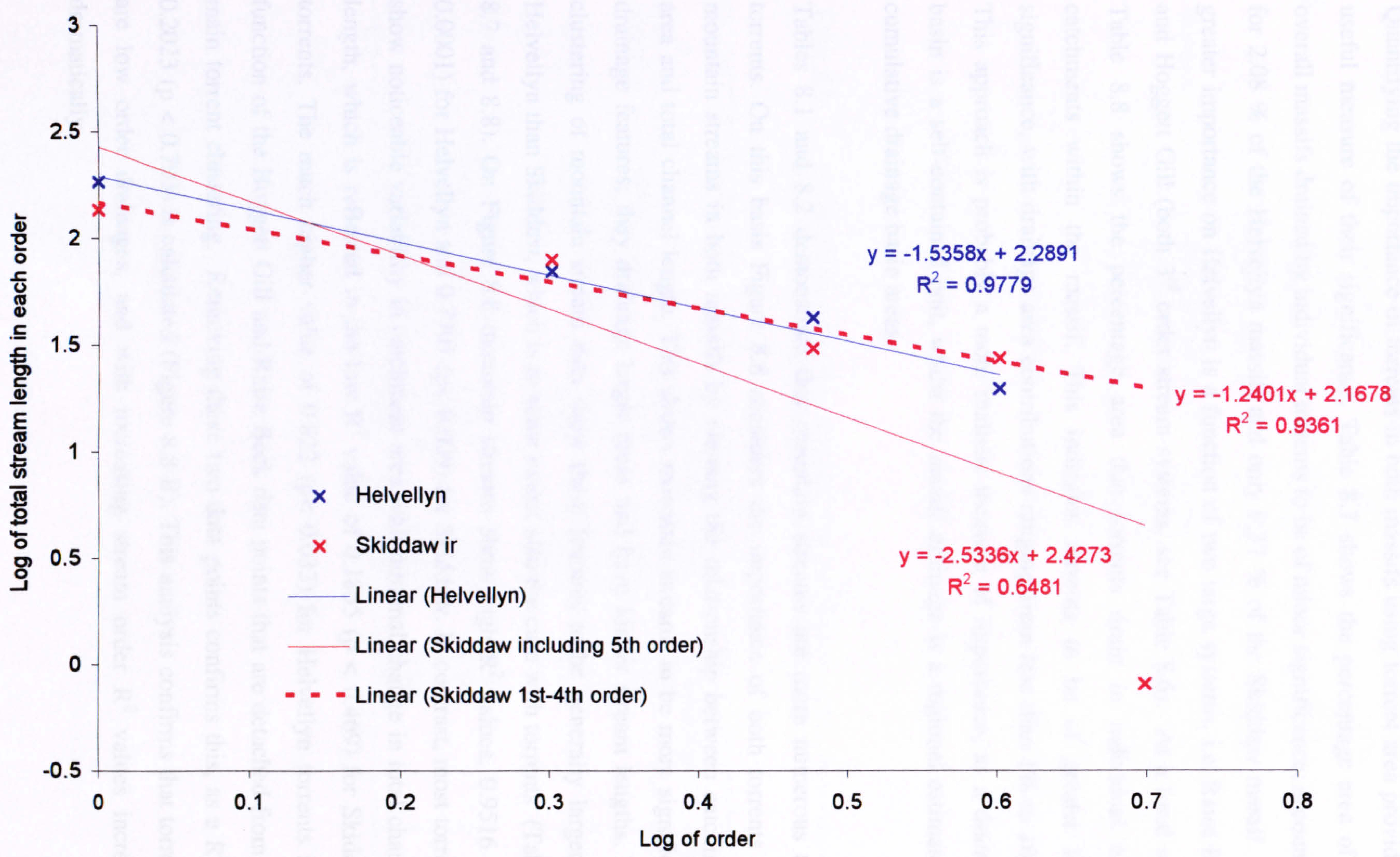
Table 8.5: A comparison of the drainage morphometry of the Helvellyn and Skiddaw massifs

Massif	Stream order (Strahler, 1957)	Number of stream segments	Sum length (km)	Percentage length	Massif area (km^2)	Drainage density (km km^2)
Helvellyn					120.6	2.6
	1	794	183.92	58.0		
	2	189	70.27	22.2		
	3	35	42.60	13.5		
	4	8	19.81	6.3		
	ALL	*1026*	*316.61*			
					128.5	2.1
Skiddaw						
	1	676	135.93	49.5		
	2	160	79.86	29.1		
	3	35	30.54	11.1		
	4	9	27.53	10		
	5	2	0.81	0.3		
	ALL	*882*	*274.68*			

Table 8.6: The stream order classification of torrents in the Helvellyn and Skiddaw massifs

Massif	Torrent	Stream order range
Helvellyn	Fairfield Brow	1
	Hoggett Gill	1-3
	Wintergroove Gill	1-2
	Rydal Fell	1
	Raise Beck	1-3
Skiddaw	Barkbethdale South	1
	Tongues Beck	1-2
	Foul Gill	1
	Bannerdale Crags	1
	Iron Crag	1

Figure 8.7: Regression of stream length on stream order



that these first order streams correspond to the greatest total catchment area, or indeed that torrents dominate first order drainage systems.

Quantifying the importance of torrents in both massifs using torrent area provides a useful measure of their significance. Table 8.7 shows the percentage area of the overall massifs drained by individual torrents to be of minor significance; accounting for 2.08 % of the Helvellyn massif; and only 0.37 % of the Skiddaw massif. The greater importance on Helvellyn is a function of two large systems, i.e. Raise Beck and Hoggett Gill (both 3rd order stream systems, see Table 8.6). At a local scale Table 8.8 shows the percentage area that torrents drain in individual basin catchments within the massif. This indicates torrents to be of greater local significance, with drainage area contributions ranging from less than 1% to 100%. This approach is probably a more realistic measure of importance, as a drainage basin is a self-contained unit, whilst the massif drainage is a regional estimate of cumulative drainage basin areas.

Tables 8.1 and 8.2 demonstrate that mountain streams are more numerous than torrents. On this basis Figure 8.8 considers the importance of both torrents and mountain streams in both massifs by viewing the relationship between catchment area and total channel length. This shows mountain streams to be more significant drainage features; they drainage larger areas and have longer stream lengths. The clustering of mountain stream data show these features to be generally larger on Helvellyn than Skiddaw, which is to some extent also the case with torrents (Tables 8.7 and 8.8). On Figure 8.8 mountain streams show high R^2 values, 0.9516 ($p< 0.0001$) for Helvellyn and 0.7701 ($p< 0.009$) for Skiddaw. In contrast, most torrents show noticeable variability in catchment area with minimal change in total channel length, which is reflected in the low R^2 value of 0.1855 ($p < 0.469$) for Skiddaw torrents. The much higher value of 0.822 ($p< 0.033$) for Helvellyn torrents is a function of the Hoggett Gill and Raise Beck data points that are detached from the main torrent clustering. Removing these two data points confirms this, as a R^2 of 0.2023 ($p < 0.703$) is calculated (Figure 8.8 B). This analysis confirms that torrents are low order drainages, and with increasing stream order R^2 values increase dramatically.

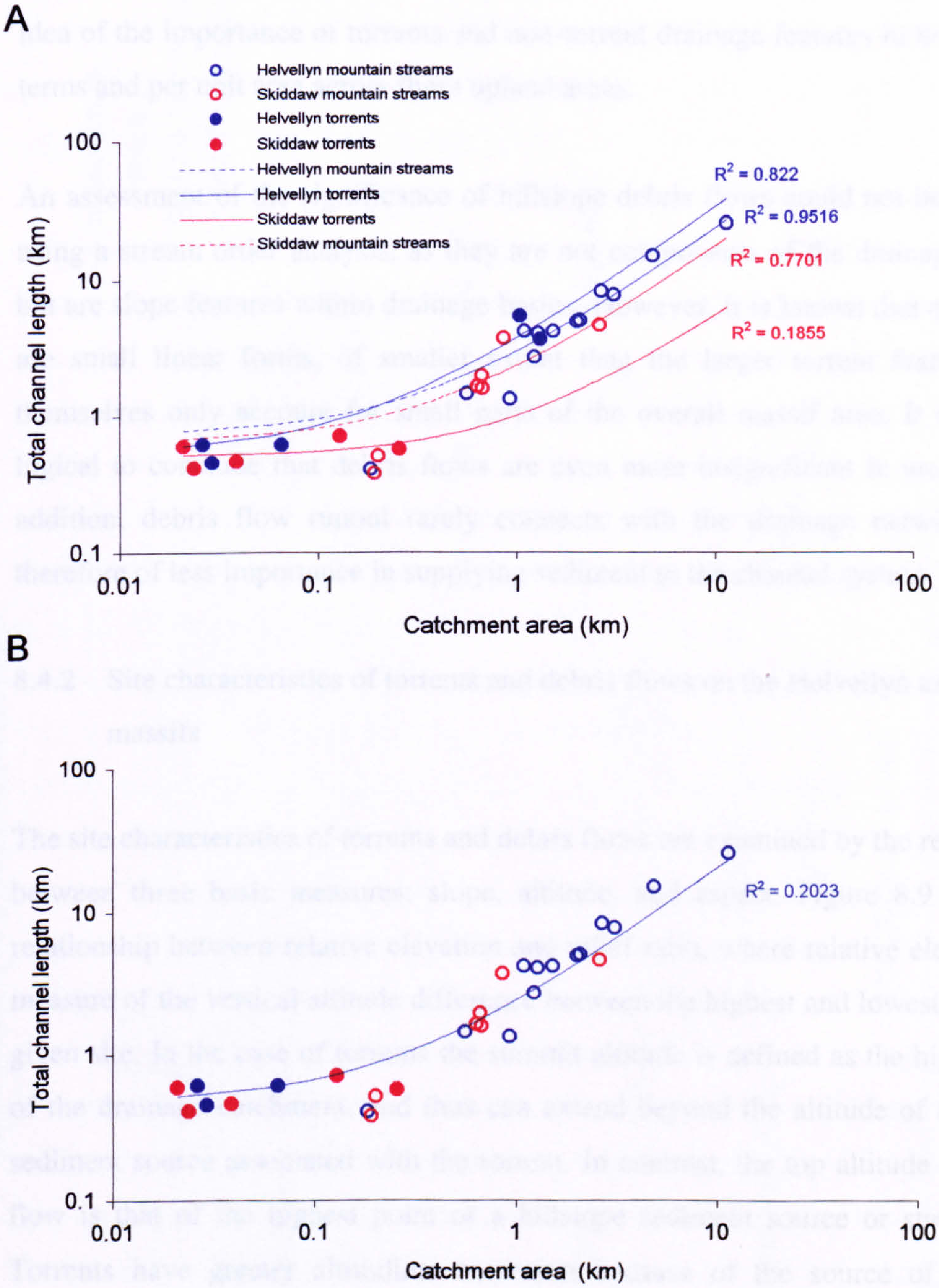
Table 8.7: The significance of torrents in the Helvellyn and Skiddaw massifs, measured as a function of the total massif area.

Massif	Torrent	Torrent area (Km^2)	Percentage of total massif area
Helvellyn	Fairfield Brow	0.0266	0.020
	Hoggett Gill	1.0558	0.876
	Wintergroove Gill	0.0665	0.055
	Rydal Fell	0.0296	0.025
	Raise Beck	1.3300	1.103
	Sum of torrents	*2.5085*	*2.080*
Skiddaw	Barkbethdale South	0.0392	0.031
	Tongues Beck	0.2600	0.202
	Foul Gill	0.1308	0.102
	Bannerdale Crags	0.0211	0.016
	Iron Crag	0.0240	0.019
	Sum of torrents	*0.4751*	*0.370*

Table 8.8: The significance of torrents in the Helvellyn and Skiddaw massifs, measured as a function of the drainage basin areas in which torrents are located.

Massif	Torrent	Drainage basin area (Km^2)	Torrent area (Km^2)	Percentage of total basin area	Highest stream order
Helvellyn	Fairfield Brow	3.817	0.0266	0.697	1
	Hoggett Gill	6.673	1.0558	15.822	3
	Wintergroove Gill	3.258	0.0665	2.041	2
	Rydal Fell	8.664	0.0296	0.342	1
	Raise Beck	1.330	1.3300	100	3
Skiddaw	Barkbethdale South	6.535	0.0392	0.599	1
	Tongues Beck	2.770	0.2600	9.386	2
	Foul Gill	9.506	0.1308	1.376	1
	Bannerdale Crags	11.138	0.0211	0.189	1
	Iron Crag	9.881	0.0240	0.243	1

Figure 8.8: Relationship between catchment area and stream length in torrent and mountain stream ctachments
(A) Inclusive of Hoggett Gill and Raise Beck
(B) Exclusive of Hoggett Gill and Raise Beck



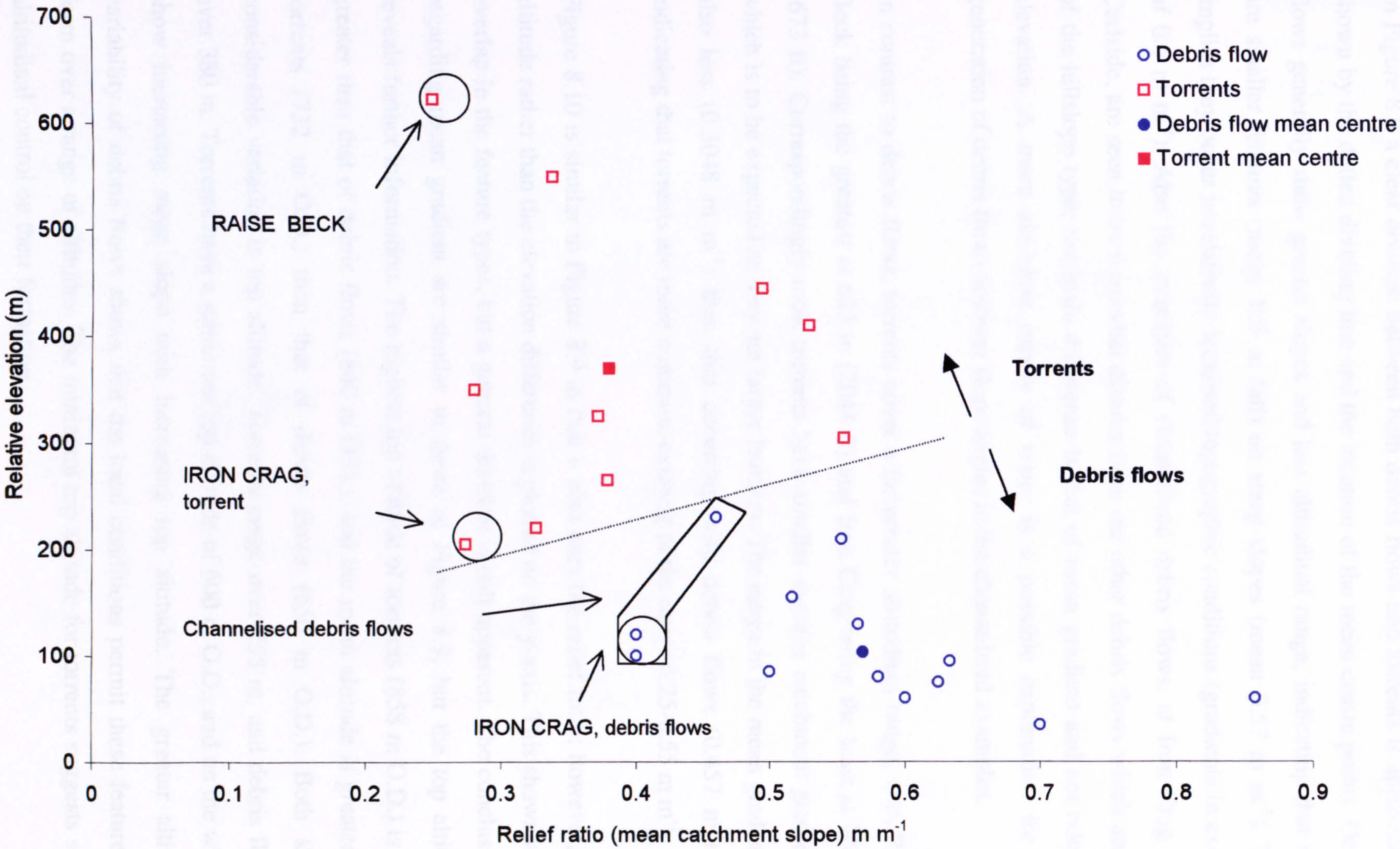
It is has been demonstrated that torrents can be locally important, but over a broader area they are largely insignificant, whilst mountain streams are more important in area terms in the Helvellyn and Skiddaw massifs. Developments to this preliminary investigation could include quantification of sediment yield and 'work' calculations (e.g. Caine 1976; Warburton, 1993). These approaches would give a more informed idea of the importance of torrents and non-torrent drainage features in both absolute terms and per unit area across these upland areas.

An assessment of the significance of hillslope debris flows could not be performed using a stream order analysis, as they are not components of the drainage network, but are slope features within drainage basins. However, it is known that debris flows are small linear forms, of smaller extent than the larger torrent features which themselves only account for small parts of the overall massif area. It is therefore logical to conclude that debris flows are even more insignificant in area terms. In addition, debris flow runout rarely connects with the drainage network, and is therefore of less importance in supplying sediment to the channel system.

8.4.2 Site characteristics of torrents and debris flows on the Helvellyn and Skiddaw massifs

The site characteristics of torrents and debris flows are examined by the relationships between three basic measures: slope, altitude, and aspect. Figure 8.9 shows the relationship between relative elevation and relief ratio, where relative elevation is a measure of the vertical altitude difference between the highest and lowest points at a given site. In the case of torrents the summit altitude is defined as the highest point of the drainage catchment, and thus can extend beyond the altitude of the highest sediment source associated with the torrent. In contrast, the top altitude of a debris flow is that of the highest point of a hillslope sediment source or starting zone. Torrents have greater altitudinal extension because of the source of water via overland flow, whereas debris flows have clearly defined sediment source zones. In both cases the basal altitude is that defined by the lowest deposit, be it a debris flow levee/ lobe terminus or fan toe. Relief ratio is a term defined by Schumm (1956) and Strahler (1964) to be the ratio of the difference between the maximum and minimum

Figure 8.9: Relationship between relief ratio and relative elevation for torrents and debris flows in the Helvellyn and Skiddaw massifs



altitudes and maximum length measured along the main valley line. This is more commonly known as the mean catchment gradient or slope.

In Figure 8.9 a clear division between both debris flows and torrents is apparent, as shown by the dotted dividing line and the location of the mean centre points. Debris flows generally show greater slopes and less altitudinal range, indicating that they are smaller features (mean 103 m fall) on steep slopes (mean 0.57 m m^{-1}). This implies they occur in relatively localised topographic conditions (gradients in excess of 0.4 m m^{-1}). Also the examples of channelised debris flows, at Iron Crag and Carlside, are seen to be somewhat distinct from the other debris flows which are all of the hillslope type; the main difference is that of mean gradient and not relative elevation. A more abundant supply of water is a possible explanation for the generation of debris flows at lower slope angles in the channelised examples.

In contrast to debris flows, torrents cover a far greater altitudinal range, with Raise Beck being the greatest at 623 m (2044 ft) and Iron Crag being the least at 205 m (673 ft). Correspondingly most torrents have smaller average catchment gradients, which is to be expected as they are larger features. The range in the mean gradient is also less (0.3048 m m^{-1}) than that occurring with debris flows (0.457 m m^{-1}), indicating that torrents are more common, existing in the range 0.25-0.55 m m^{-1}.

Figure 8.10 is similar to Figure 8.9 in that it also uses the relief ratio; however, top altitude rather than the elevation difference is plotted on the y-axis. This shows some overlap in the feature types, but a general division is still apparent. The conclusions regarding mean gradient are similar to those of Figure 8.9, but the top altitude reveals further information. The highest top altitude of torrents (858 m O.D.) is just greater than that of debris flows (840 m O.D.), and the mean altitude is greater for torrents (732 m O.D.) than that of debris flows (650 m O.D.). Both show considerable variation in top altitude. Torrents range over 258 m, and debris flows over 380 m. Torrents have a minimum top altitude of 600 m O.D., and on the whole show increasing mean slope with increasing top altitude. The greater altitude variability of debris flows shows that the local conditions permit these features to form over a range of altitudes. The minimum top altitude for torrents suggests some altitudinal control on their formation.

Figure 8.10: Relationship between relief ratio and top altitude for torrents and debris flows in the Helvellyn and Skiddaw massifs

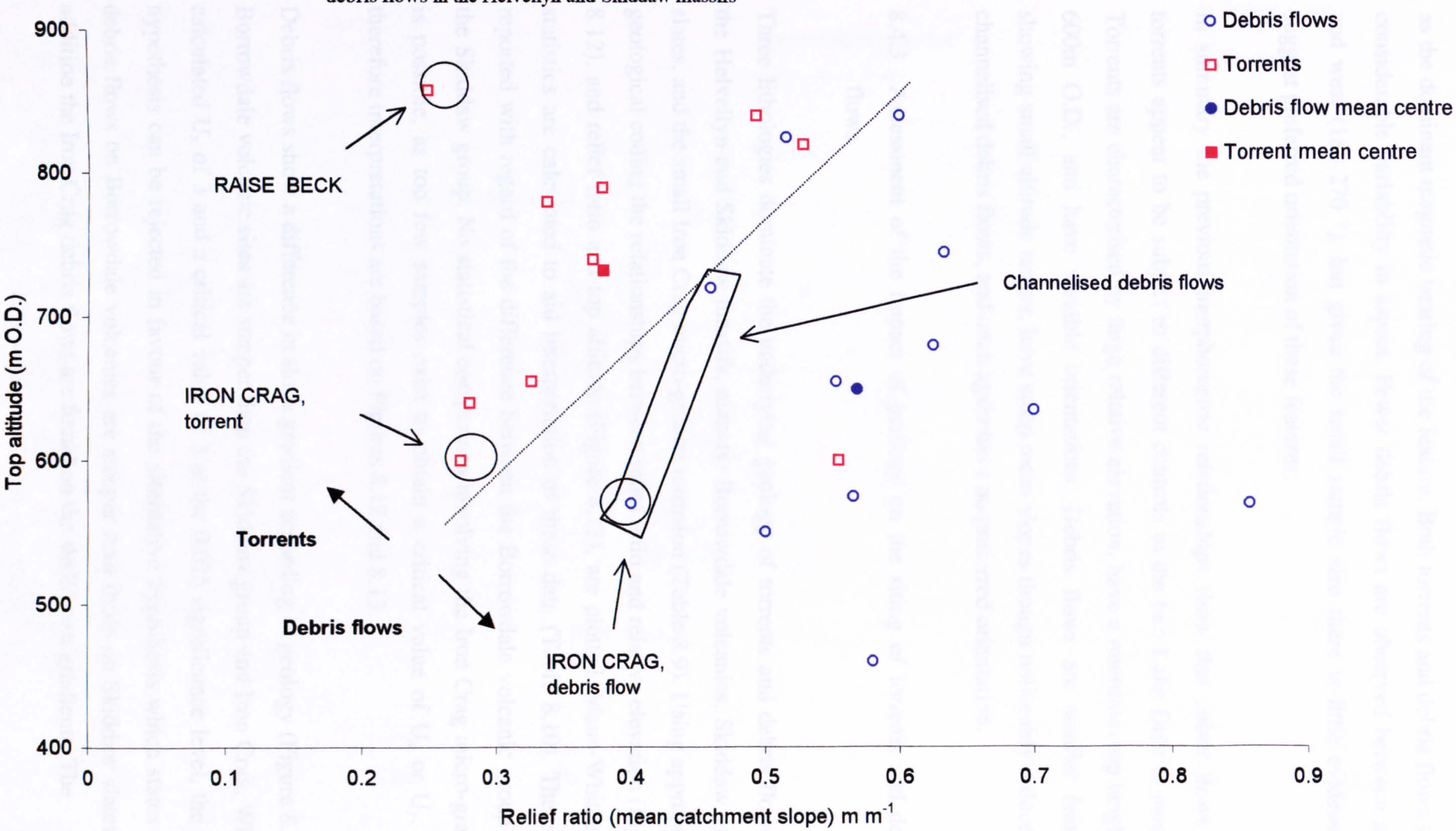


Figure 8.11 shows the relationship between relief ratio and aspect, the latter defined as the dominant magnetic bearing of the feature. Both torrents and debris flows show considerable variability in aspect. Fewer debris flows are observed between south and west (180-270 °), but given the small sample size there is little evidence to suggest preferred orientation of these features.

In summary the previous morphometric relationships show that debris flows and torrents appear to be subject to different controls in the two Lake District massifs. Torrents are characterised by large relative elevation, have a minimum top height of 600m O.D., and have variable orientations. Debris flows are smaller features showing small altitude ranges, have steep mean slopes though noticeably reduced in channelised debris flows, and once again have no preferred orientation.

8.4.3 Assessment of the impact of geology on the siting of torrents and debris flows

Three lithologies dominate the underlying geology of torrents and debris flows on the Helvellyn and Skiddaw massifs, namely: Borrowdale volcanics, Skiddaw group slates, and the small Iron Crag micro-granite intrusion (Table 8.9). Using appropriate geological coding the relationships between relief ratio and relative elevation (Figure 8.12), and relief ratio and top altitude (Figure 8.13), are plotted. Mann-Whitney U statistics are calculated to aid interpretation of these data (Table 8.10). These are reported with regard of the difference between the Borrowdale volcanic group and the Skiddaw group. No statistical comparison involving the Iron Crag micro-granite is possible, as too few samples exist to obtain a critical value of U_x or U_y, and therefore interpretations are based on Figures 8.12 and 8.13.

Debris flows show a difference in slope gradient according to geology (Figure 8.12). Borrowdale volcanic sites are steeper than the Skiddaw group and Iron Crag. With a calculated U_x of 3 and a critical value of 3 at the 0.025 significance level, the null hypothesis can be rejected in favour of the alternative hypothesis which states that debris flows on Borrowdale volcanics are steeper than those on Skiddaw slates. In addition the Iron Crag debris flows are found on the shallowest gradients. The

Figure 8.11: Relationship between relief ratio and aspect for torrents and debris flows in the Helvellyn and Skiddaw massifs

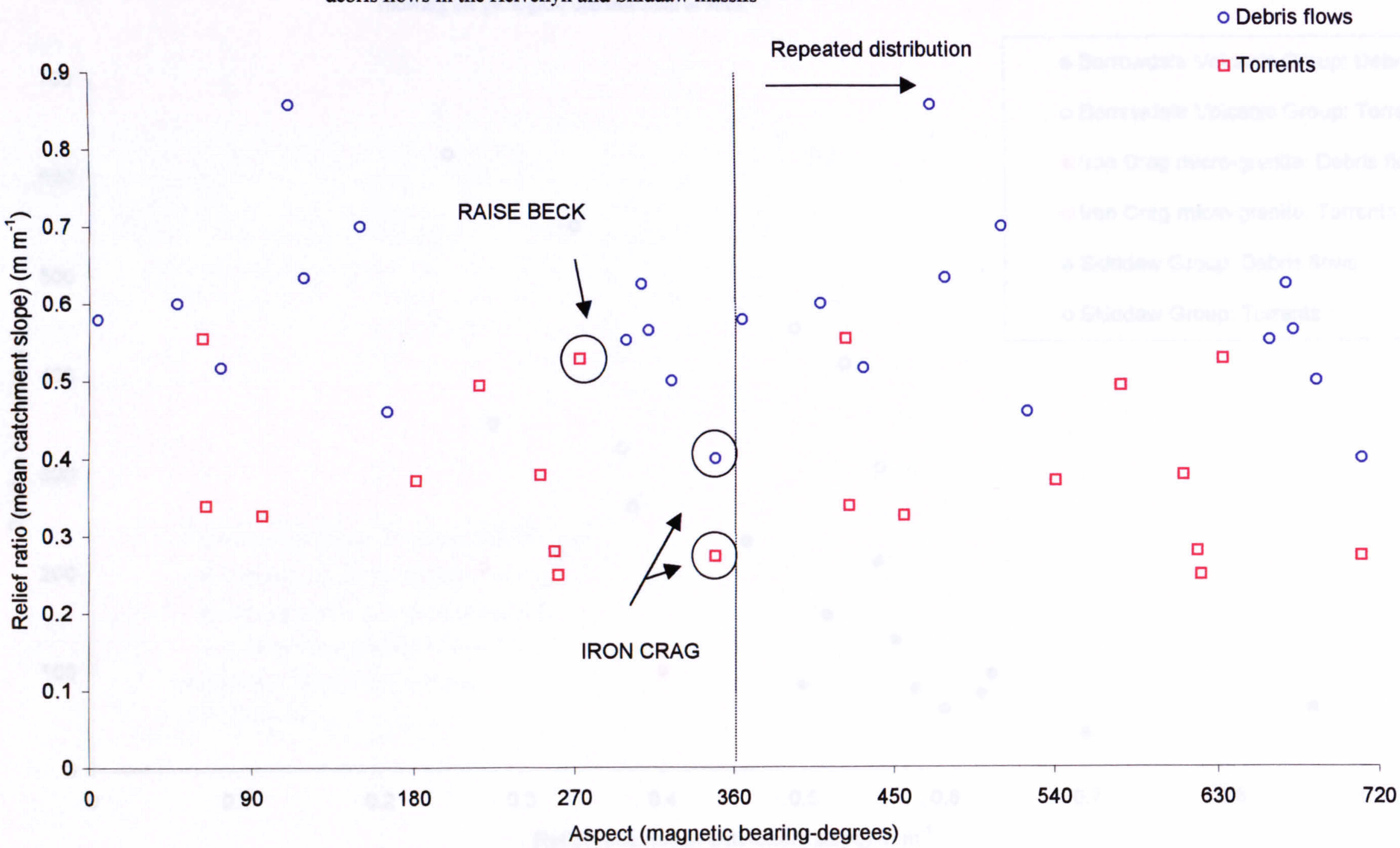


Figure 8.12: Relationship between relief ratio and relative elevation showing the geological classification of sites

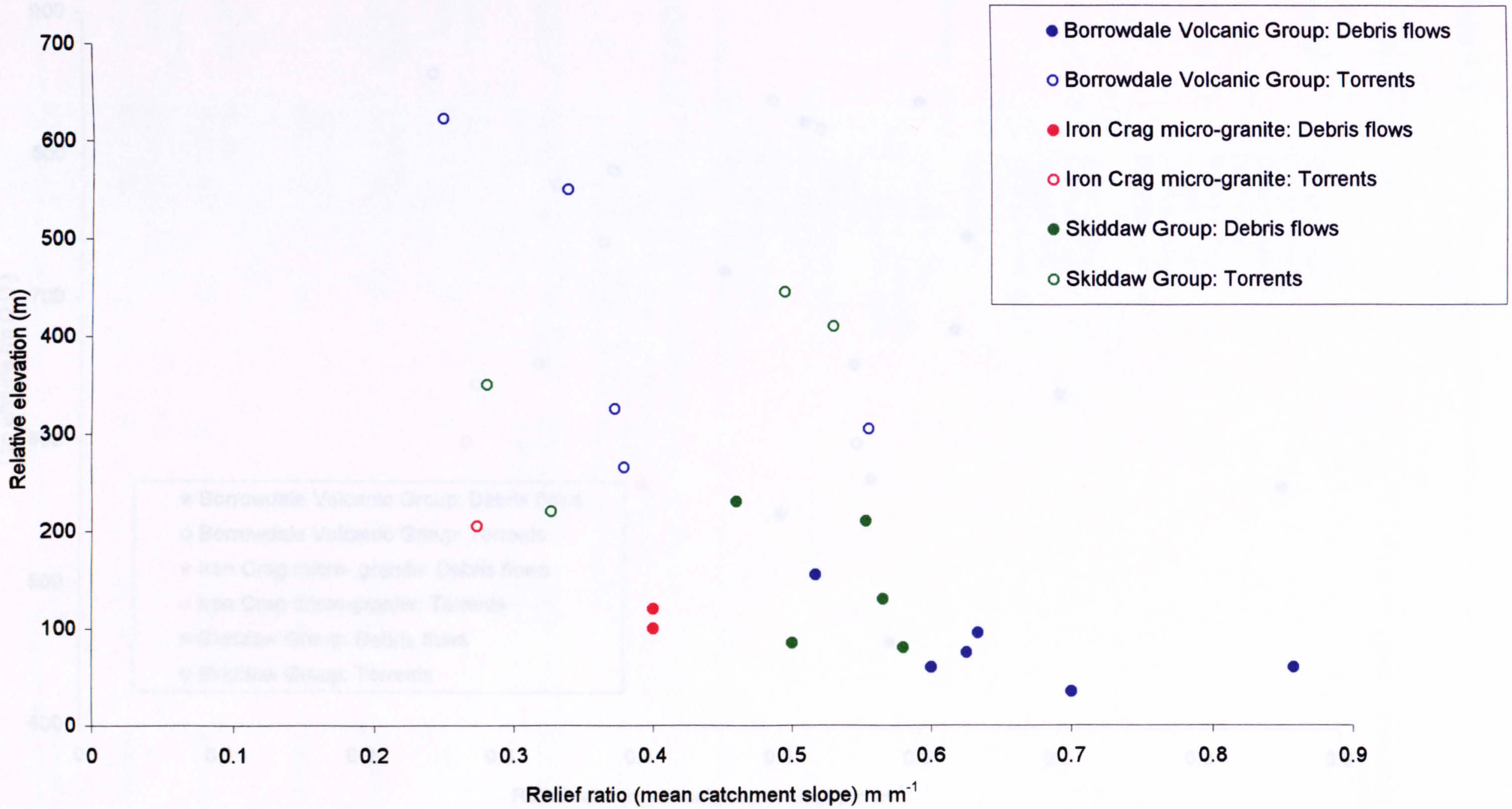


Figure 8.13: Relationship between relief ratio and top altitude showing the geological classification of sites

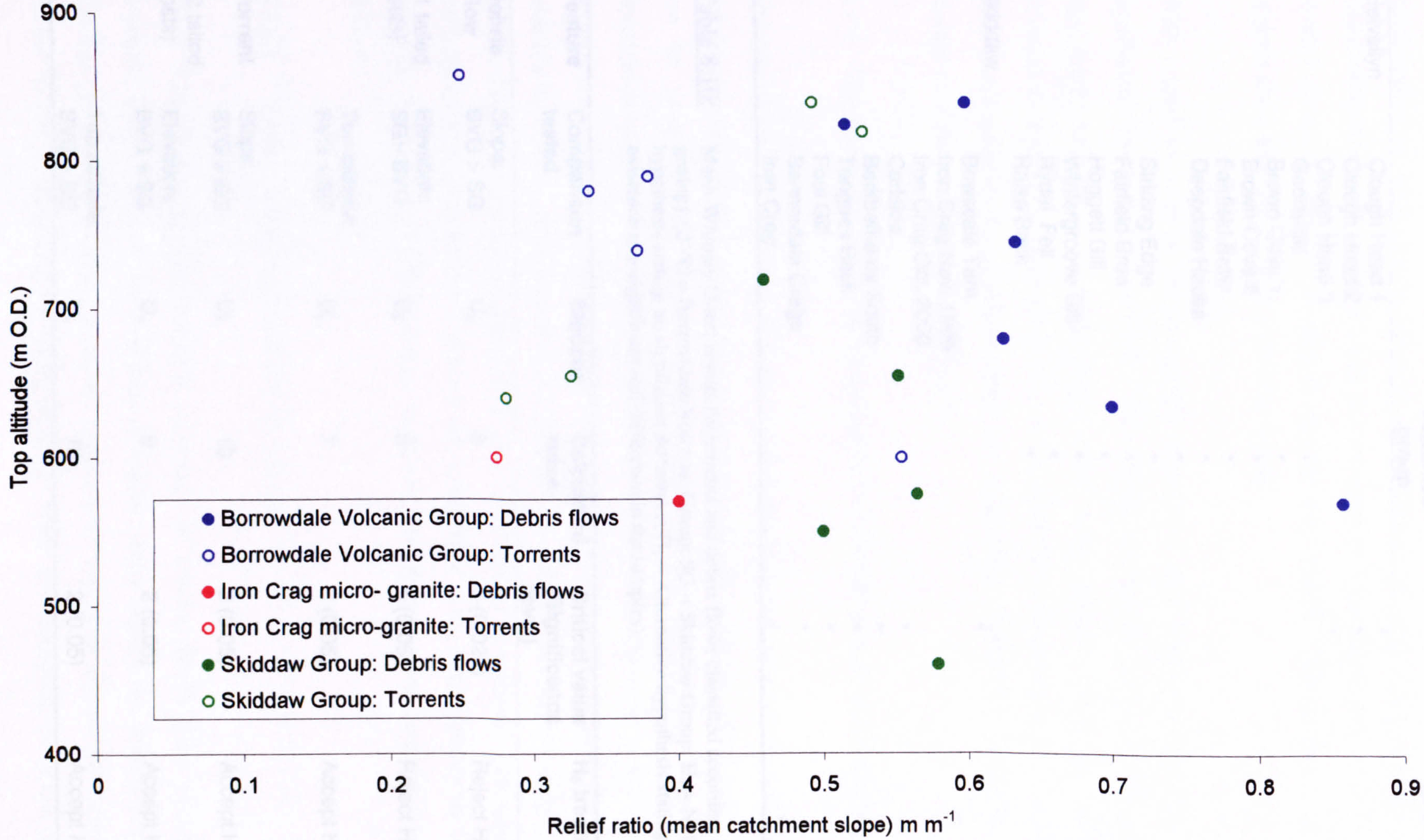


Table 8.9: General solid geology classification of torrents and debris flows identified on the Helvellyn and Skiddaw massifs

Massif	Site	Borrowdale volcanics group	Skiddaw group	Iron Crag micro-granite
Helvellyn	Clough Head 1		*	
	Clough Head 2		*	
	Clough Head 3		*	
	Geenside	*		
	Brown Cove 1	*		
	Brown Cove 2	*		
	Fairfield Brow	*		
	Deepdale Hause	*		
		*		
	Striding Edge	*		
	Fairfield Brow	*		
	Hoggett Gill	*		
	Wintergroove Gill	*		
	Rydal Fell	*		
	Raise Beck	*		
Skiddaw				
	Bowscale Tarn		*	
	Iron Crag Nov. 1999			*
	Iron Crag Oct. 2000			*
	Carlside		*	
	Barkbethdale South		*	
	Tongues Beck		*	
	Foul Gill		*	
	Bannerdale Crags		*	
	Iron Crag			*

Table 8.10: Mann-Whitney U-test results for torrents and debris flows classified according to geology (BVG = Borrowdale Volcanic Group; SG = Skiddaw Group; H_0 = Null hypothesis stating no significant difference; H_1 = Alternative hypothesis stating the existence of a significant real difference in the samples)

Feature	Comparison tested	Statistic	Calculated value	Critical value (Significance level)	H_0 treatment
Debris Flow	Slope: BVG > SG	U_x	3	3 (0.025)	Reject H_0
(1 tailed tests)	Elevation: SG> BVG	U_x	5	5 (0.05)	Reject H_0
	Top altitude: BVG > SG	U_x	7	6 (0.05)	Accept H_0
Torrent	Slope: BVG ≠ SG	U_x	10	2 (0.05)	Accept H_0
(2 tailed tests)	Elevation: BVG ≠ SG	U_x	9	2 (0.05)	Accept H_0
	Top altitude: BVG ≠ SG	U_x	10	2 (0.05)	Accept H_0

relative elevation of debris flows (Figure 8.12) is greater on Skiddaw slates than Borrowdale volcanics, a difference that is confirmed at the 0.05 significance level. The Iron Crag features show a relative elevation that is comparable with both of the main geologies. However, in the case of top altitude (Figure 8.13) no statistically significant difference occurs between the two main geologies at the 0.05 significance level; both occupy similar altitudes, though the Borrowdale Volcanics do occupy the highest sites, and the Skiddaw slates the lowest.

With regard to torrents, no statistically significant differences occur at the 0.05 significance level (see Table 8.10). This shows that torrents have no statistically significant differences in morphology (relief ratio; relative elevation; and top altitude) with geology. Geology is not a strong control on the siting of torrents. With such small samples these relationships are suggestive rather than definitive and require confirmation with a larger data set.

8.4.4 Magnitude and frequency characteristics of torrent systems and debris flows

The magnitude and frequency of flood events in torrents and debris flow movements can be assessed for sites where suitable field evidence is available. Event magnitude can be assessed from flow velocity reconstructions. In torrents, velocity is determined using boulder diameters from fluvial deposits in channels or fans, whilst debris flow velocity is obtained from levee super-elevation (see section 8.3.3). In addition to velocity, discharge is also calculable for debris flows but not torrents, as palaeo-channel geometry information is often incomplete in torrents. Estimates of the frequency of large events in torrents are established using lichenometry on flood deposits. Absence of lichen coverage on debris flow deposits prevents this type of analysis.

8.4.4.1 Torrent event magnitude and frequency

Table 8.11 shows the reconstructed velocities of torrent floods from preserved deposits. The deposits reflect evidence of events whose impact has persisted in the channel system since initial formation, and as such represent significant formative events in the development of these torrents. With the exception of Raise Beck

(Chapter 7) events are largely characterised by flows in the range 3-4.5 m s^{-1}. More precise measures of event magnitude ideally require the calculation of discharge, as these flow velocities could have been associated with different flow widths and depths. Also a better context for these palaeo-events requires knowledge of the whole range of flow velocities and discharges generated in these torrents. Neither are available without direct measurement.

Table 8.11: Magnitude of torrent floods reconstructed from preserved fluvial deposits

Site	Boulder deposit	Mean b-axis size of 5 largest boulders (mm)	Velocity using Equation 8.3 (m s^{-1})
Wintergroove Gill	A- right bank	570	3.96
	A- left bank	704	4.39
	B	320	2.99
	C	286	2.83
	D	440	3.49
Hoggett Gill	A	399	3.33
	B	377	3.24
	C	360	3.16
	D	470	3.60
Rydal Fell	1	770	4.58
	2	400	3.33
	3	636	4.17
	4	574	3.97
Tongues Beck	A	546	3.88
	B1 RIDGE a	344	3.09
	B1 RIDGE b	648	4.21
	B2	466	3.59
	D	305	2.92
	E	280	2.80
	G	376	3.23
Foul Gill	A	584	4.00
Raise Beck 1995 flood maximum	B17	1418	6.17

Lichenometric age dating of flood deposits in five torrents is outlined in Table 8.12. Deposits are dated in the age range 17-19 to 222-240 years (baseline 1999). The majority of the flood units are in excess of 100 years old. As with the Raise Beck flood deposits in Chapter 7, deposits with similar ages are grouped into flood units representing single flood events. Table 8.13 shows that there is little overlap between flood unit ages. Even with the addition of ± one standard deviation most flood units

Table 8.12: Ages of Helvellyn and Skiddaw torrent flood deposits derived using lichenometry (baseline 1999. The ages reported are obtained from the growth rates of [A] Macklin *et al.*, 1992; and [B] Merrett and Macklin, 1999.

Site	Boulder deposit	Mean size of 5 largest lichens	Age A (years)	Age B (years)
Wintergroove Gill	A- RB	41.8	107	116
	A- LB	41.8	107	116
	B	6.8	17	19
	C	-	-	-
	D	39	100	108
Hoggett Gill	A	79.8	205	222
	B	71.2	183	198
	C	76.4	196	212
	D	86.4	222	240
Rydal Fell	1	43.8	112	122
	2	-	-	-
	3	-	-	-
	4	53.6	137	149
Tongues Beck	A	35.2	90	98
	B1 RIDGE a	55.5	142	154
	B1 RIDGE b	71.6	184	199
	B2	54	138	150
	D	38	97	106
	E	32.6	84	91
	G	35.4	91	98
Foul Gill	A	47	121	131

Table 8.13: Summary of probable flood unit ages relative to 1999. (Where the standard deviation is calculated from a data set composed of the ages prescribed to all boulder deposits in each particular flood unit).

Site	Probable flood unit	Maximum age (a)	Minimum age (a)	Mean age (a)	Standard deviation (a)
Wintergroove Gill	WG 1	116	107	112	5.20
	WG 2	108	100	104	5.66
	WG 3	19	17	18	1.41
Hoggett Gill	HG 1	240	222	231	12.73
	HG 2	222	196	209	11.00
	HG 3	198	183	191	10.61
Rydal Fell	R 1	149	137	143	8.49
	R 2	122	112	117	7.07
Tongues Beck	TB 1	199	184	192	10.61
	TB 2	154	138	146	7.30
	TB 3	106	90	97	5.79
	TB 4	91	84	88	4.95
Foul Gill	FG 1	131	121	126	7.07

remain independent. Only three overlaps occur, namely WG 1-2; HG 1-2; and TB 3-4. This suggests that the ages of flood units at each site are independent, and belong to different flood events. It is also seen that the standard deviation increases with the age of deposit, showing that the precision of dating older deposits is less. This is reflected in Table 8.13, where older deposits are grouped more broadly.

The field evidence for the flood units of each torrent are now considered to assess the feasibility of the age relationships. Figure 8.14 illustrates Wintergroove Gill (site 56) and the flood units preserved at the apex and mid point of the fan. Deposits A, right and left bank are both the same age, and form flood unit WG 1. WG 2 which is slightly younger (by 8 years, mean age) is seen downstream of WG 1, which means for this unit to be deposited water had to overtop units WG 1 without disturbing them. Given this observation two conclusions can be drawn; firstly, it is unlikely that water and sediment would overtop WG 1 and leave it insitu without scaring or removing the older lichens. Thus both units would have to relate to the same flood event, despite the small difference in lichen diameter. An alternative explanation is that WG 2 is formed by flow reworking sediment beyond the base of WG 1, which would allow WG 1 to be an older deposit. WG 3, is a young (18 years) mid-channel bar deposit situated along the contemporary channel course.

Figure 8.15 considers the Hoggett Gill (site 48) basal fan flood deposits. The highest surface of the fan is a central terrace that contains a sheepfold. This is considered to be the oldest feature of the fan, as younger deposits are associated with lower surface elevations that have incised the fan surface leaving the terrace feature. Deposit D forms HG 1 the oldest flood unit on the right bank side of the fan. This suggests that in c. 1768 the channel occupied the right bank side of the fan surface. It is speculated that the left bank side of the fan contained no flow at this time. The younger deposits which comprise the left side of the fan have a smaller mean b axis (Table 8.11) than those found in deposit D. Thus, if any deposits of the same age and size as deposit D existed on the left bankside of the fan, the younger events would have been incapable of transporting them. Therefore, by implication, the absence of deposits today probably suggest that none were there to start with. This assumes that older deposits were not undermined or indeed buried by younger events. Following this reasoning HG 2 represents a flood avulsion in about 1790, with the larger HG 3 deposits (Table 8.11) (c. 1808) being a subsequent partial reworking of this deposit or indeed a fresh one. The first edition Ordnance Survey map for Westmorland (c. 1863) (Old Maps, 2000) shows the main channel to the right of the fan, so this avulsion appears to have been either an overbank flood event, or more likely a short-lived reversal in channel position occurring prior to 1863.

Figure 8.16 shows the Rydal Fell torrent (site 60), with most of the deposits positioned immediately above the fan apex at the end of the main torrent channel. Flood unit R2, associated with deposit 1, is the younger of the two deposits. This is considered to be an independent unit as it is higher up the fan than unit R1. Age control is established for unit R1, by a wall intersecting the fan. It is known from the first edition Ordnance Survey map of Westmorland (Old Maps, 2000) that the wall existed in 1863, and large *Rhizocarpon* sp. lichens on it today suggest it has remained unchanged since then. Behind the wall the fan surface has aggraded, and on this general aggradation surface lie the boulders of deposit 4, classified as flood unit R 1. The estimated date of R1 around 1856 is considered to be fairly accurate as the wall probably existed some time prior to 1863 allowing the aggradation of the fan surface and the subsequent deposit of R1.

Figure 8.17 shows the field interpretation and aerial photographs of Tongues Beck and fan (site 8). All B series deposits on the right bank side of the current channel are the oldest dateable deposits in the system. These form flood units TB 1 and TB 2. Downstream and on the opposite banks deposits A, G and D form one flood unit (TB 3). All the deposits are at a similar elevation. It is therefore suggested that the flood flow that created TB 3 was diverted around flood units TB 1 and TB 2. The youngest deposit is towards the toe of the fan and is thought to have incised an area of older deposits which are of unknown age.

Figure 8.14: Wintergroove Gill (A) fan fluvial deposit field sketch map (not to scale); (B) Oblique aerial photo (7.5.00); (C) Ground view of system (22.1.00)

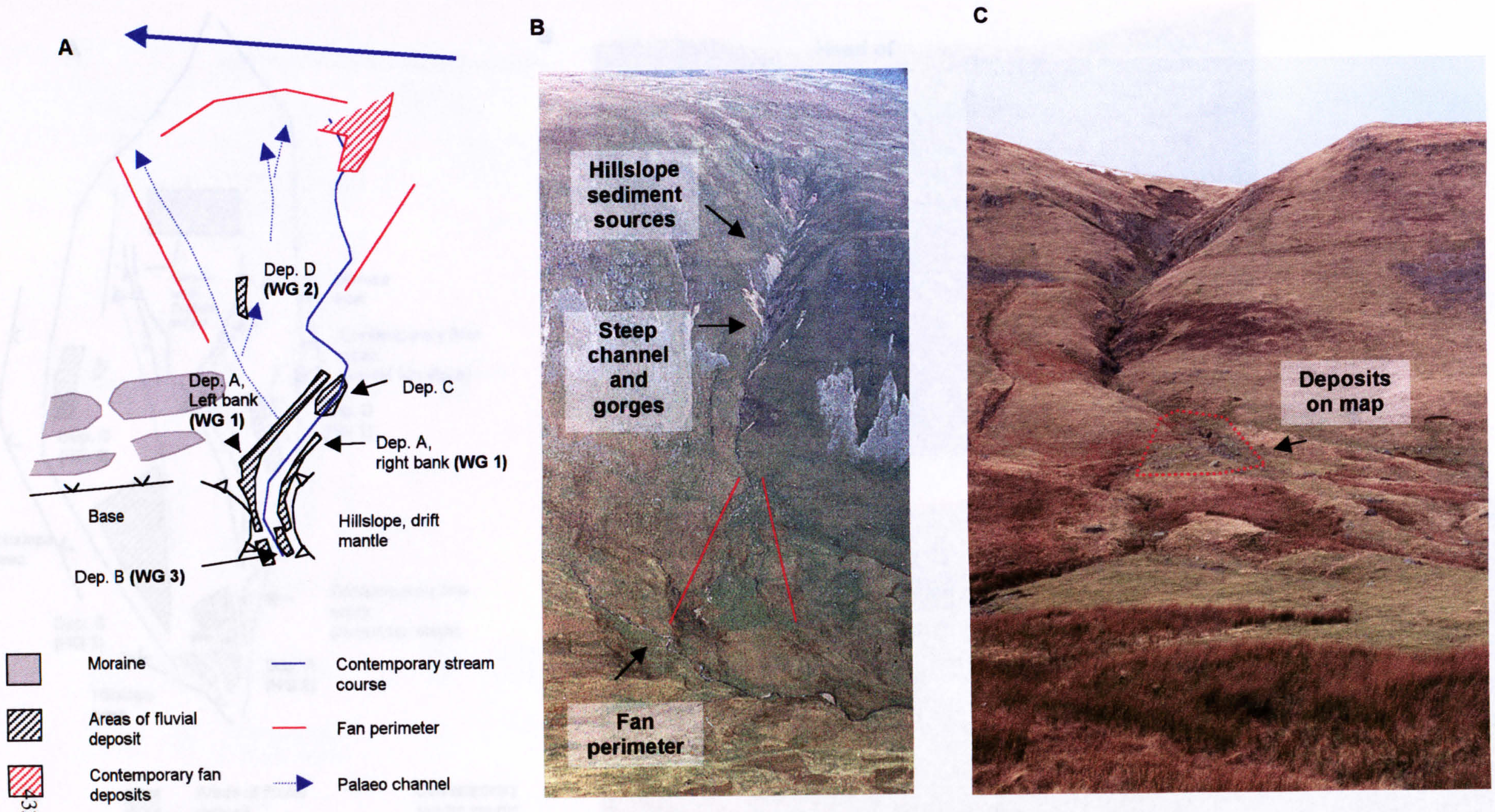
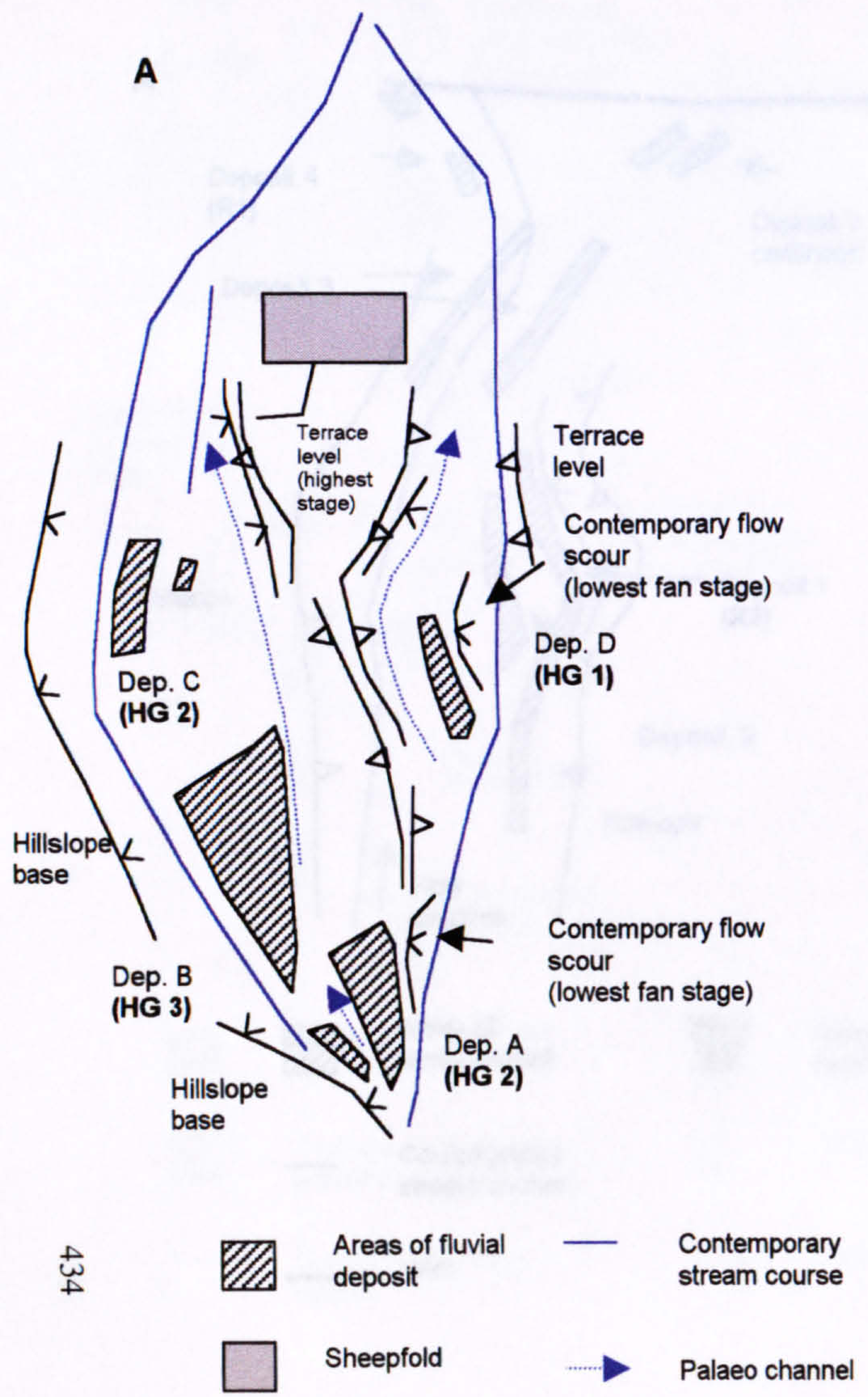
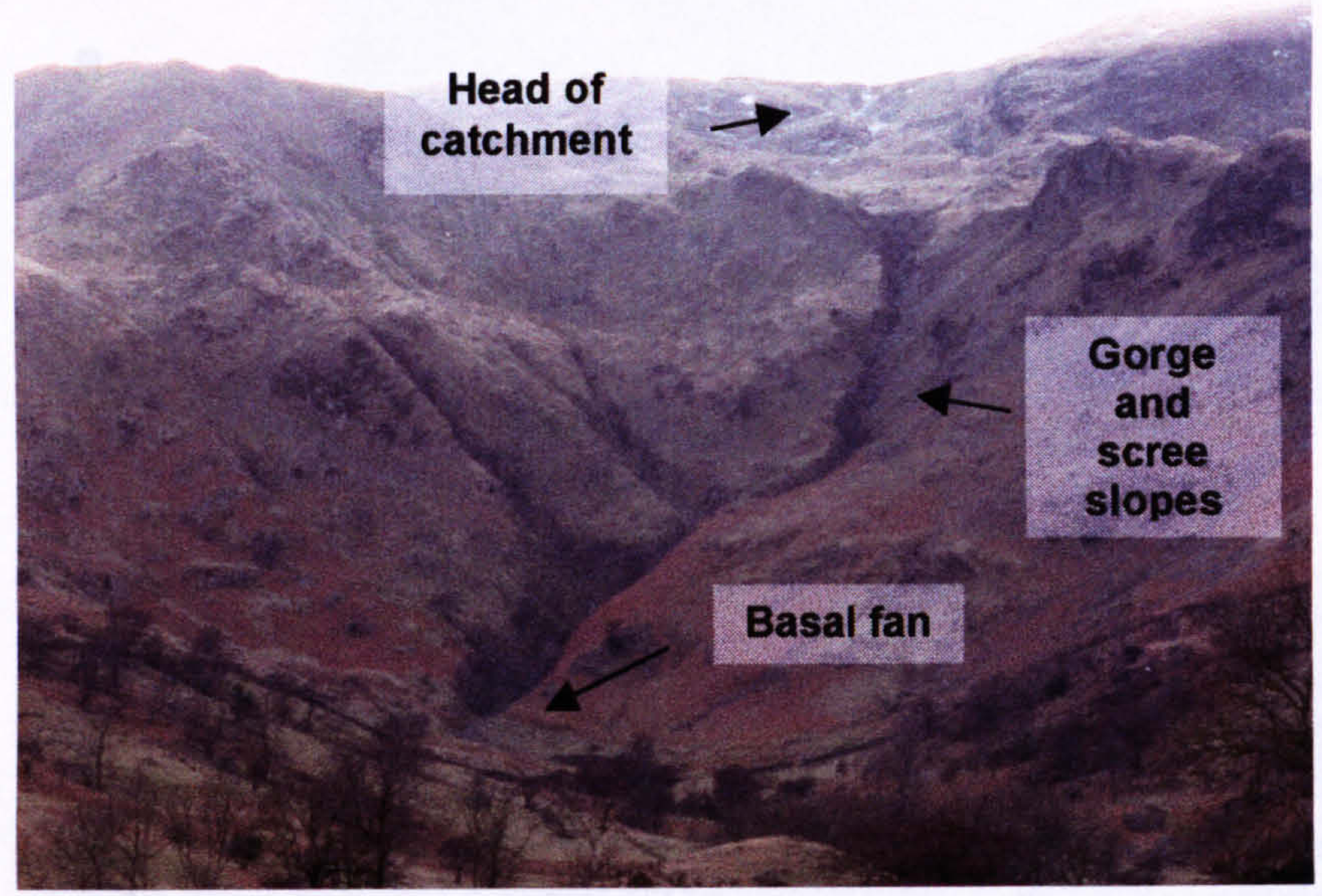


Figure 8.15: Hoggett Gill (A) fan deposit field sketch map (not to scale); (B) Hoggett Gill torrent; (C) Fan

A



B



C

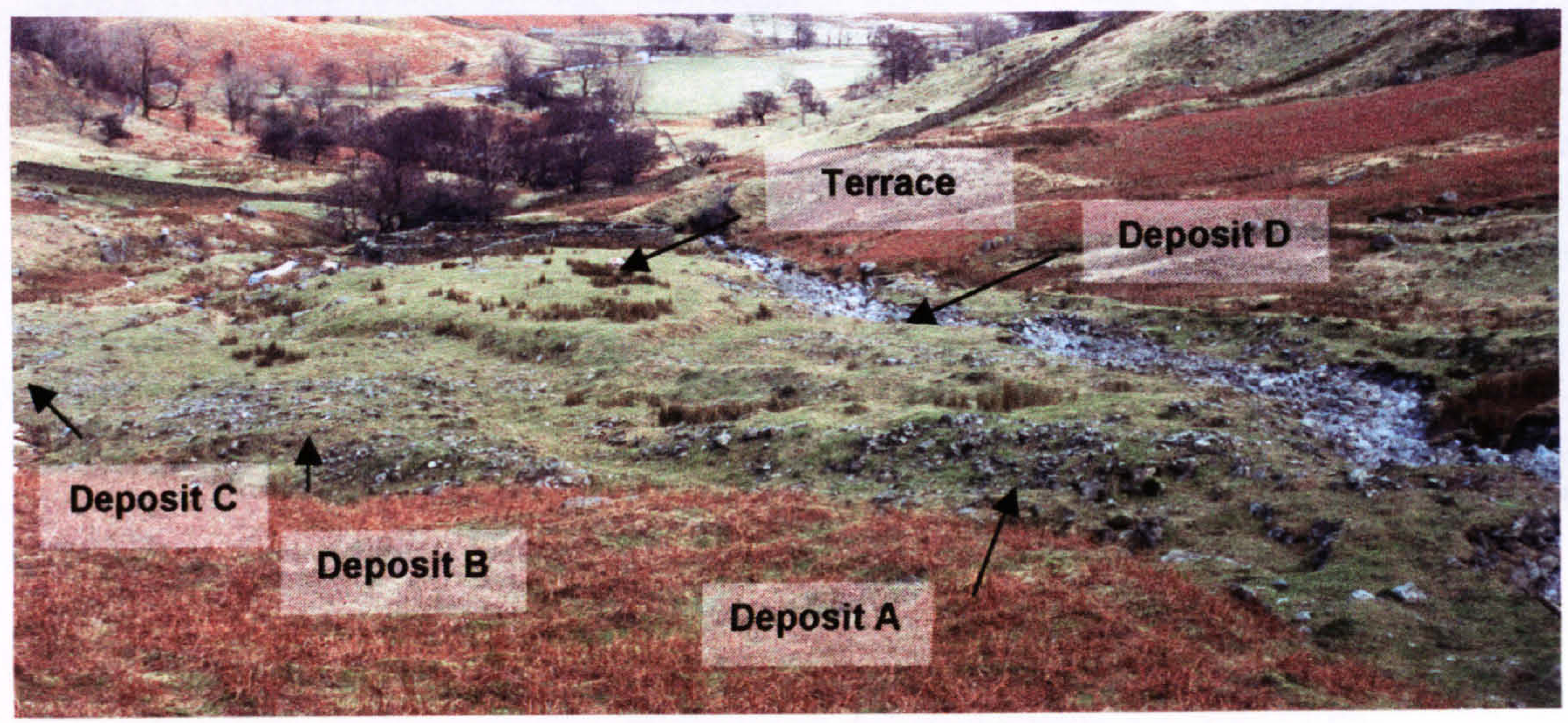


Figure 8.16: Rydal Fell (A) fan apex fluvial deposit sketch map (not to scale); (B) Oblique aerial view (7.5.00); (C) Fan and deposits (19.1.00)

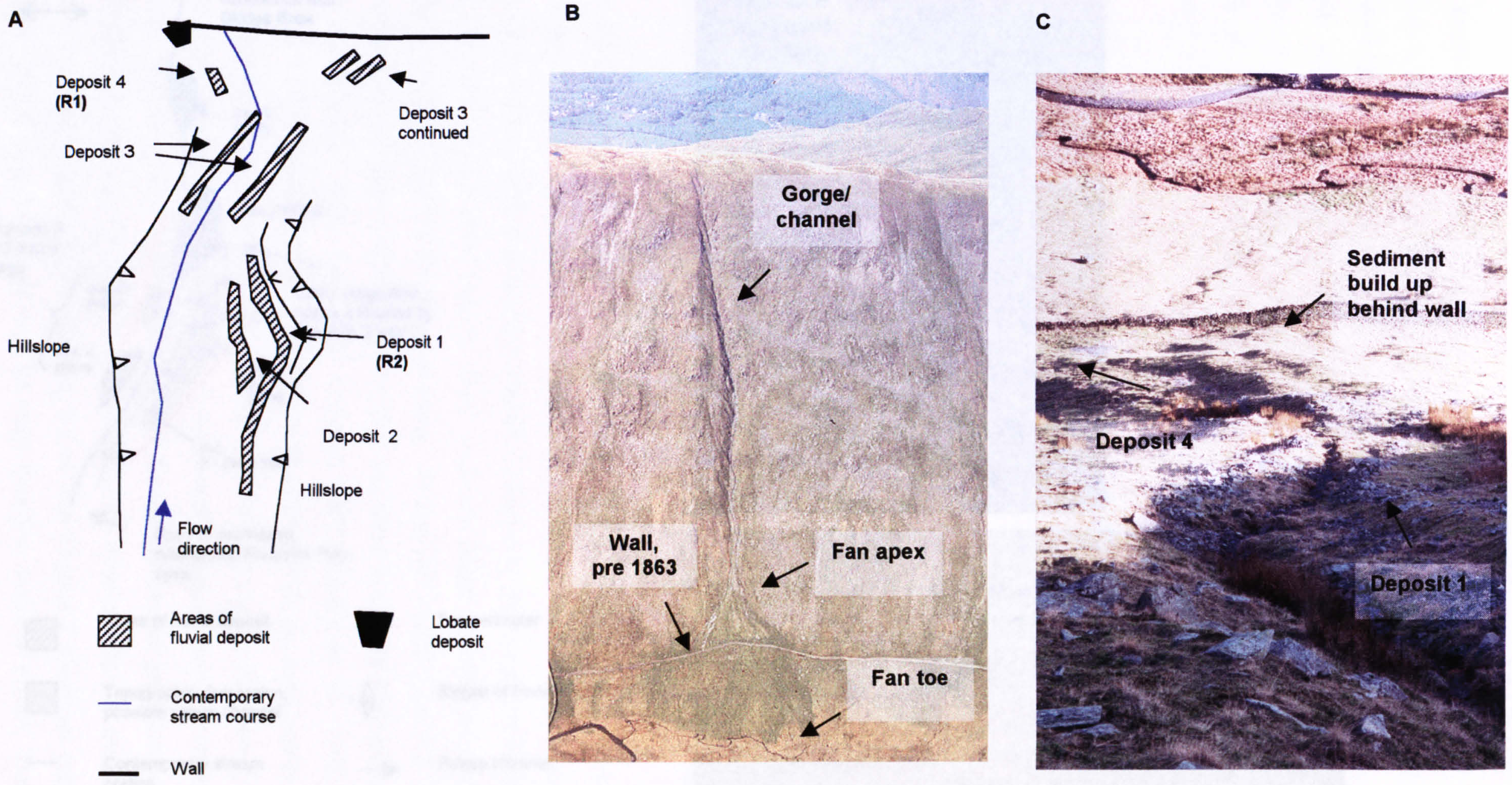
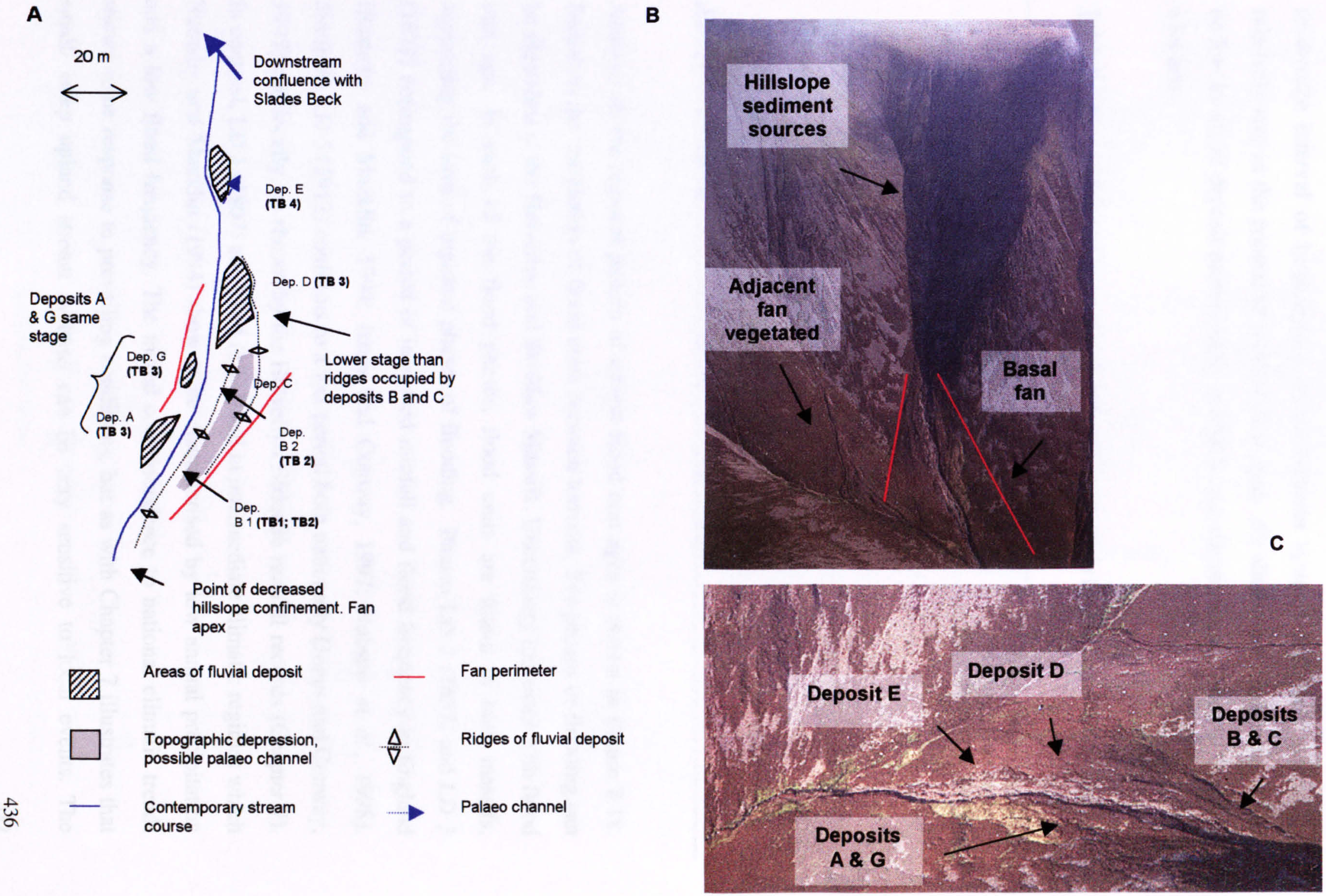


Figure 8.17: Tongues Beck (A) fan fluvial deposit map, based on vertical photograph; (B) Oblique aerial view of system (16.10.99); (C) Oblique aerial of fan (16.10.99)



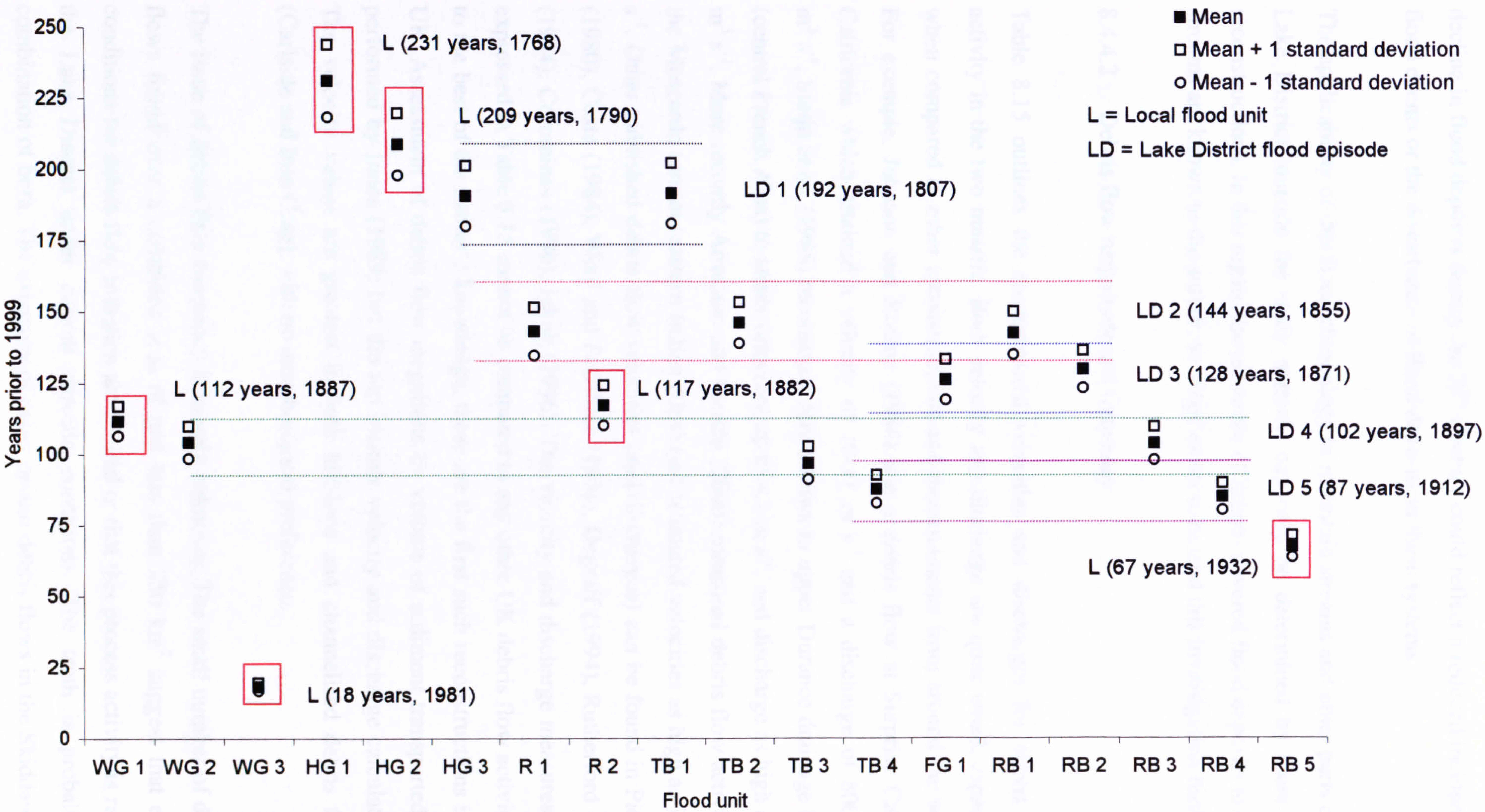
Having established that the sequence of flood units at the sites are valid, it is possible to calculate a simple index of frequency of occurrence (based on the oldest flood unit age divided by the number of flood units [Table 8.14]). This demonstrates that the recurrence interval of large events varies between systems and such events are relatively rare in the context of a human life-span. An alternative explanation could be low levels of deposit preservation, in which case the recurrence interval could be a lot less.

Table 8.14: Estimation of the frequency of large flood events in Lake District torrents, based on reconstructions of flood unit age.

Site	Maximum age range (years)	Number of flood units	Crude mean return period of formative datable events (years)
Wintergroove Gill	112	2/3	37.33/ 56
Hoggett Gill	231	3	77
Rydal Fell	143	2	71.5
Tongues Beck	192	4	48
Foul Gill (no morphological verification possible)	126	1	126

Analysis of the regional pattern of torrent flood unit ages is shown in Figure 8.18. Based on the correlation of flood units between torrents, five phases of flooding can be identified in the Helvellyn and Skiddaw Massifs. Uncertainty increases with flood unit age. In each of the flood phases, flood units are found in both massifs, supporting the idea of regional phases of flooding. Phases LD 2 (1855) and LD 3 (1871) correspond to a period of increased rainfall and flood frequency in England (Rumsby and Macklin, 1994; Jones and Conway, 1997; Robson *et al.*, 1998). Similarly LD 5 (1912) conforms to a wet period both nationally (Jones and Conway, 1997) and locally, as shown by the Helvellyn Birkside rainfall records (Chapter 7). In contrast, LD 1 (1807) and LD 4 (1897) fall in intermediate climatic regimes which Rumsby and Macklin (1994) show to be characterised by low annual precipitation and a low flood frequency. The mixed correspondence to national climatic trends shows some response to prevailing conditions, but as with Chapter 7 illustrates that small/ steep upland stream systems can be very sensitive to local events. The

Figure 8.18: Correlation of torrent flood units across the Skiddaw and Helvellyn massifs showing the mean age of local and regional flood deposits



decline in flood deposits during the 20th Century could reflect a reduced incidence of flood events or the disturbance of flood deposits in these systems.

The applicability of this flood chronology to mountain streams and other parts of the Lake District, outside the study massifs, can only be determined by more field reconstructions. In this regard the existence of lichen- covered flood deposits in other streams are known to the author, so scope exists to extend this investigation further.

8.4.4.2 Debris flow magnitude and frequency

Table 8.15 outlines the reconstructed velocities and discharges for debris flow activity in the two massifs. Both velocity and discharge are quite small, especially when compared to other reconstructions and measurements from around the world. For example, Johnson and Rodine (1984) cite a debris flow at Surprise Canyon California which attained a velocity of 10-11 m s^{-1} and a discharge of 800-900 m^3 s^{-1}. Steijn *et al.* (1988) reconstruct debris flows in upper Durance drainage basin (central French Alps) to attain velocities up to 4.2 m s^{-1}, and discharge as high as 89 m^3 s^{-1}. More recently Arrattano and Marchi (2000) measured debris flow activity in the Moscardo torrent (eastern Italian Alps) and estimated velocities as high as 7.9 m s^{-1}. Other published debris flow velocities (and discharges) can be found in Pierson (1980), Costa (1984), Wohl and Pearthree (1991), Degraff (1994), Rutherford *et al.* (1994), Corominas (1996), Jakob (1996). The velocity and discharge measurements expressed in Table 8.15 cannot be compared to any other UK debris flow activity as, to the best of the author's knowledge, these are the first such reconstructions in the UK. Assessment of debris flow magnitude by volume of sediment transported was performed by Innes (1989) but did not include velocity and discharge calculations. The velocity values are greatest in both hillslope and channelised debris flows (Carlside and Iron Crag), with no morphological preference.

The issue of debris flow frequency is largely unknown. The small number of debris flows found over a combined area of just less than 250 km^2 suggest that either conditions for debris flow initiation are limited or that this process activity is rare in the Lake District under current climatic conditions. The truth is probably a combination of both. The existence of many palaeo-debris flows in the Skiddaw and

Helvellyn massifs and other areas of the Lake District are evidence that debris flows were more common in the past. Hence it is probable that under current conditions hillslope debris flows are low frequency events.

Table 8.15: Magnitude of debris flow activity reconstructed from preserved super-elevated levee deposits

Site	Mean velocity (m s^{-1})	Discharge (m^3 s^{-1})
Carlside	0.951	0.82
	0.879	0.70
Clough Head 1	1.287	0.74
Brown Cove 2	1.739	4.43
	1.186	1.74
Deepdale Hause	1.250	1.12
Falcon Crag	1.594	3.58
Iron Crag (November 1999)	1.714	1.09
Iron Crag (October 2000)	1.585	2.74
	1.170	1.08

Interestingly however, in less than 12 months Iron Crag produced two channelised debris flows, and further small hillslope debris flows. This may be a reflection of the high rates of process activity at this site. The debris flow levees following the November 1999 event remained in the channel for about a month, until they were modified by fluvial activity. This suggests the channel recovers quickly and removes the evidence of debris flow activity. Thus the frequency of debris flows may be greater in the Lake District than indicated at any one time. As with the study of torrents a broadening of the investigation to other parts of the Lake District and palaeo-debris flow features will provide a larger data set, enabling more substantive conclusions to be reached.

8.4.5 A comparison of Iron Crag and Raise Beck to other sites in the region.

The comparison of Raise Beck and Iron Crag to other regional sites has been considered in previous sections. Here a synthesis of these observations is provided.

Raise Beck is a very good example of a high-order torrent dominated by fluvial process activity. It is the largest of all the torrents in the 250 km^2 survey area (1.33 km^2), having the largest catchment area contribution to both a massif (1.1 %) and an individual drainage basin (100 %), plus the greatest top altitude (858 m O.D.) and relative elevation difference (623 m). It has the lowest mean slope of 0.249-m m^{-1}, and attains third order status. The underlying solid geology is the Borrowdale volcanic group, the same as all Helvellyn massif torrents. In terms of process activity, Raise Beck has the largest reconstructed velocity of any torrent, at 6.17 m s^{-1}. This is associated with deposits from the January 1995 event. The fact that these flood deposits are fresh allows the selection of the largest boulders from a large population. Older deposits have varying amounts of vegetation cover, therefore reducing the number of boulders available for measurement. This could possibly result in an underestimation of event velocity. Furthermore, the use of flood deposits on a fan is likely to yield smaller b-axis sizes, as particle size decreases downstream. These factors may account for Raise Beck having a greater reconstructed flood velocity than other torrents. However, it is known from the Helvellyn Birkside rain gauge (Chapter 7) that the January 1995 flood occurred in the wettest month since records began in 1866. The frequency of effective flooding at Raise Beck is the greatest of all torrents (5 site specific flood units), and it is represented in four of the regional flooding phases, namely LD 2, 3, 4 and 5.

Iron Crag is a torrent with a channel dominated by fluvial process activity, but also with occasional debris flows. It is amongst the smallest of torrents, with the second smallest catchment area (0.024 km^2), though it is similar to 6 other torrents (Table 8.3). It has the lowest top altitude of 600 m O.D. and the smallest elevation range of 205 m, which is noticeably less than most other torrents except Bannerdale Crags and Fairfield Brow. Reflecting this small size, only first order drainage is identifiable from the OS 1: 25,000 map. In relation to debris flow activity it has the lowest slope recorded (0.4 m m^{-1}) but an average relative elevation of around 100 m. Geologically Iron Crag is a unique torrent, being the only one situated on the Iron Crag micro-granite complex.

In terms of debris flows, they are most frequent at Iron Crag, but of similar velocity and discharge to other Lake District debris flows. The higher frequency of debris flows at Iron Crag may be a product of the detailed site monitoring, or due to the local site conditions of abundant sediment supply and the flashy response to rainfall events. Evidence of palaeo-activity is not present in the form of boulder deposits, as the local rock disintegrates into granular-sized material rather than large boulders. This is not, however, to say that flood episodes have not occurred in the past, as the fan stratigraphy and recent aerial photography show (Chapter 6).

8.5 Conclusions of regional study

This study has demonstrated the general characteristics of both torrents and debris flows in the Helvellyn and Skiddaw Massifs. It has also provided a context in which to assess the case study sites at Iron Crag and Raise Beck.

Morphometric and geological controls are to some extent evident in the siting of torrents and debris flows. Torrents exhibit greater altitudinal extent and lower relief ratios than debris flows, which appear to be small, steep, localised features. Debris flows have greater slope on Borrowdale volcanic rocks, and least on the Iron Crag micro-granite complex. Geology, however, imparts no significant control over the siting of torrents.

The need for more detailed study has been illustrated with regard to establishing:

a) The importance of torrents and mountain streams, by using 'work' calculations and sediment yield. The former requires channel cross sectional measurements from many systems; the latter needs monitoring of sediment yield.

b) The magnitude and frequency of velocity and discharge of flows in torrents. This requires the installation of permanent weirs to measure the stage of water.

c) To verify the regional chronology of past flood activity, more reconstructions are required across the Lake District, in all stream types.

d) To provide a broader understanding of debris flow activity, more reconstruction is required over a wider study area, of recent and palaeo debris flow forms.

The implication of the need to conduct more analysis is that the foregoing investigation must be considered as a pilot study, which has provided new evidence on UK torrents and debris flows. It has shown that torrents are dominated by fluvial process activity, and that the expression of debris flows at the other end of the sediment-water flow spectrum is rare in UK torrents, although this may be because the evidence of debris flow activity is short-lived, or specific material conditions are required (e.g. Iron Crag). Debris flow activity in the Lake District has been found overwhelmingly on hillslopes, where activity is small scale and probably of low frequency.

CHAPTER 9: SUMMARY AND CONCLUSIONS

9.0 Study overview

The aim of this study was to investigate processes of torrent erosion in Lake District mountain catchments, considering both fluvial and debris flow activity, and to establish the spatial and temporal aspects of these processes. A nested research approach was adopted. A detailed investigation was undertaken at Iron Crag using a sediment budget approach to determine the spatial and short-term temporal aspects of process activity. Particle size analysis was used to investigate the diagnostic characteristics of meteorologically-driven hillslope processes, and to reconstruct recent and historical fan process activity. Reconstruction of fluvial flood events in the Raise Beck torrent produced evidence of recent and historical high-magnitude flood events. A regional survey of torrent, mountain stream and debris flow (channelised and hillslope) characteristics provides an overall spatial and temporal context for the detailed case study investigations at both Iron Crag and Raise Beck. The empirical results of this work form the main body of the thesis, in which the following main objectives were investigated:

1. Quantify sediment supply, transport and storage in an active torrent over an annual timescale.

2. Determine the role of different meteorological events in controlling torrent erosion processes.

3. Establish a long-term chronology of process activity in a torrent, to give a context for the contemporary process investigations.

4. Investigate the frequency and impact of high magnitude sediment-water flow events in a torrent catchment.

5. Examine the regional attributes and significance of torrents and hillslope debris flows in two areas of contrasting geology.

This chapter summarises the main findings of this thesis before providing an overall synthesis. This links together the main findings, considers broader issues of geomorphology and landform development, and compares the results to other studies of similar systems. A brief consideration of the impact of land use and climate changes on upland/ torrent erosion is given. This is followed by a discussion of the limitations of the study, and an outline of suggestions for further research.

9.1 Summary of the empirical research

9.1.1 Sediment budget of the Iron Crag torrent system

Research conducted between 12th December 1998 and 7th December 1999 provides an annual sediment budget for the Iron Crag torrent system. This is based on the monitoring of system components, including surface wash and rockfall from hillslope sediment sources, bank erosion, channel bed changes, and sedimentation and erosion of the basal fan. The sediment budget model is presented in two formats: firstly, in terms of total annual sediment yield (t a^{-1}) (Figure 5.3), and specific sediment yield (kg m^{-2} a^{-1}) (Figure 5.4). Figure 5.3 shows the channel bed to be the dominant sediment source accounting for 70 % of sediment yield to the fan apex. The remainder is composed of 25 % from banks adjacent to the channel, and 5% from the hillslopes. Figure 5.4, does however, show that when the area of each process component is considered the significance of banks is as great as the channel, 195 kg m^{-2} a^{-1} and 233 kg m^{-2} a^{-1} respectively. Figure 5.3 shows 70 % of the hillslope contribution is derived from surface wash processes and the remainder from rockfall; however, the total amount of each varies amongst the different hillslope zones. The basal fan is shown primarily to be a sediment sink, storing much of the material delivered from the net erosional activity of hillslopes, banks and channel above the fan apex.

The accuracy of the sediment budget model was assessed by evaluating some of the uncertainty in the measured components, namely survey error and transformation of volume to mass using bulk density. Maximum probable errors are the sum of these individual errors and are expressed as percentages: 21% for the channel, 31 % for the banks, and 16 % for the fan surface. Applying these values to the sediment budget components allows the question of imbalance between input (yield) and fan accretion to be investigated (Table 5.11). This is between –37 % to + 39 %, which is similar to other published results.

The temporal variability in sediment yield of each component is summarised in Figures 5.9- 5.11. Surface wash and rockfall both show a seasonal pattern, with greater yields during winter and spring and reduced yields during the summer and autumn. Bank erosion is greatest during storm events. The channel bed is generally eroded throughout the year, with greatest stability in the summer. The fan shows no strong seasonal pattern in sedimentation, but is generally linked with the channel dynamics. For example, when there is a loss of material from the channel, the fan exhibits a net gain of material, and vice versa (Figure 5.12 C). In an attempt to determine the causes of these observed changes, the relationship between component yields and meteorological variables was investigated (Figures 5.13- 5.17). It is shown that rockfall yields are positively correlated with cooler temperatures, especially the frequency of freeze-thaw cycles. Surface wash processes appear to be more complicated, which is probably a reflection of the variety of processes covered by this general term. Bank and channel erosion are greatest during periods of high rainfall (storm events), which partly explains the variability in erosion throughout the year. As the fan dynamics are strongly coupled with the channel, it is not surprising to find that fan deposition is also positively related to rainfall amount and intensity. The conclusion drawn from these results is that meteorological conditions are critical to the supply and transport of sediment in the Iron Crag system.

Detailed investigations into the significance of particular meteorological events during the sediment budget monitoring period show the impact of different event types (i.e. freeze-thaw, summer rain storm, summer dry period, autumn rainfall, and freeze-thaw with rain). Rockfall and surface wash are most active on the steeper slopes of the primary hillslope zone. In the secondary hillslope zone changing local sediment conditions influence surface wash sediment yields throughout the year (Figure 5.28). Bank erosion varies depending on the time of year; it was more active during an early summer rainstorm than for a similar event in winter. The summer event was able to remove freeze-thaw material stored from the previous winter period. The winter event occurred in the absence of a large sediment store and had only a local impact. This finding is similar to those of Newson (1980) with regard to two rare floods in mid-Wales, where ‘contingency’ influences sediment transport. Channel erosion varies in response to different types of event. For example, an autumn rainfall event triggered a channelised debris flow that resulted in extensive erosion of the channel bed. Fluvial events show variable sequences of erosion and deposition along the channel bed, reflecting differences in flow competence of the runoff events.

The overall conclusion is that the sediment dynamics of the Iron Crag torrent are largely controlled by channel and bank erosion processes, and that hillslope sediment sources play a relatively minor role. Torrent erosion processes are linked to meteorological conditions (temperature and rainfall characteristics), and the availability of sediment. Large storms have particularly significant impact on the overall sediment budget.

9.1.2 The impact of process activity on the sedimentological characteristics of hillslope deposits

A review of the literature on the sedimentary processes in steep areas established the erosional impacts of different processes. Figure 4.1 indicates whether a process will erode sediment finer or coarser than the parent material. To test these hypotheses, particle size distributions of sediment collected in Gerlach troughs and nets during the sediment budget monitoring period were analysed. In both cases a dominant process classification is applied to the deposits obtained in each measurement interval. This is based on a synthesis of field observations and meteorological records, and indicates the dominant hillslope process operating during the measurement interval. The categories identified include freeze-thaw, rainfall (term to cover all overland flow processes), dry ravel, a combination of freeze-thaw and rainfall, and composite events where no single process dominates.

Bivariate relationships between mean particle size and sediment sorting discriminate between different dominant processes (Figures 4.11, 4.15 and 4.16). Standard distance values measure the amount of scatter amongst the data of a given process and hillslope zone category. This statistic shows the greatest difference in process type, rather than the absolute plotting positions that are summarised by the mean centre values. Tables 4.6, 4.8 and 4.9 show, for both Gerlach troughs and nets, that freeze-thaw sediments are amongst the most tightly clustered, whereas sediments collected under rainfall conditions show the most scatter in both mean sediment size and sorting. Overall findings tend to refute the general hypothesis that erosional processes will generate different sediment signatures

Further understanding of process activity according to sediment source zone and seasonality is reported. The size and sorting of sediment collected in Gerlach troughs varies between the hillslope zones (Figure 4.11). Rockfall deposits in nets show less discrimination between zones (Figure 4.16), suggesting that the rockface characteristics are the main control on the size of fragments produced. Mean sediment size data for Gerlach troughs and nets reveal seasonal patterns (Figures 4.9-4.10; 4.17-4.18), generally coarser sediment in winter and spring months followed by a fining in late summer and autumn. This cycle is in phase with the annual variation in sediment yield identified by the main sediment budget study. It is therefore concluded that seasonality and hillslope source zone characteristics influence particle size characteristics, but the role of individual process is more difficult to establish.

9.1.3 Historical process activity at Iron Crag

Historical variations in stream channel and fan processes are investigated over decadal and millennial timescales, providing a context for the short-term sediment budget monitoring. A combination of aerial photographs and field observations provide information on process activity between 1953 and 2000. During this time the fan and associated channel system has been very active, with a reactivation of vegetated fan surfaces between 1953 and 1970, enhanced debris flow activity in the 1980s, and frequent fluvial activity for most of this period, but especially in the late 1990s (Figure 6.1).

Evidence of the long-term process history is obtained by examining fan sediments exposed in three pits spaced along the fan axis, from the contemporary apex to the fan toe. Stratigraphy, particle size analysis and loss-on-ignition provide a description of the fan sediments. On this basis the general process types responsible for sedimentation are determined. Pollen analysis, magnetic susceptibility and radiocarbon dating provide indications of the ages and possible causes of fan aggradation (Section 6.3).

Based on the particle size characteristics of sediment collected from deposits of known origin (type sediments), it is shown that differences in the relationship between skewness and mean size distinguish fluvial and debris flow activity (Figure 6.6). This provides a basis for classifying pit horizons into characteristic process types. Together with field observations of stratigraphy, the process activity in each horizon can be generally determined: each is identified as produced by either debris flow or fluvial activity, or alternatively considered to be fine alluvium (Figures 6.9-6.14). Some of the finest deposits are identified as palaeosols on the basis of high organic content. Variability in process activity is identified in the three pit exposures. Fluvial sedimentology dominates at the apex and toe of the fan, whilst debris flow activity is more common in the stratigraphy of the central pit.

Radiocarbon dates (SRR-6599: 6602 and AA-39694) provide the primary evidence for dating process activity, with further proxy ages inferred from pollen stratigraphy and magnetostratigraphy. The oldest deposits at Iron Crag date from 36 BC, though this is not considered to be the oldest phase of aggradation at this site. The dominant phase of aggradation of the fan occurred between 1200 and 1400 AD. Corresponding pollen evidence shows a noticeable transition from trees to heath and grasslands at this time, which is coincident with land use changes brought about Cistercian monks who converted large areas of the landscape for sheep farming. This evidence supports the hypothesis of anthropogenic forcing being the main cause of fan aggradation. However, two other widely cited factors, climate change and the impact of storm events, must also have played a role at Iron Crag. For example, the timing of the fan aggradation corresponds to the climatic deterioration recorded between 1200 and 1400 AD, whilst the presence of alternating fine and coarse sediment horizons suggests phases of stability and activity respectively. Peak values of magnetic susceptibility occur around 1400 AD; this questions the hypothesis that sediment supply from mining is a direct cause of fan sedimentation, as the main phases of mining in the area post-date this time. Using the dated stratigraphy it is shown that rates of process aggradation over the last 2000 years are greatest during the 1200-1400 AD aggradational phase (Figure 6.20), up to 11.7 mm per year. After 1400 AD rates of deposition are less than 1 mm a year. Spatial variability is also evident, with greater rates of accretion at the fan apex, declining down the fan.

A comparison of the fan chronology at Iron Crag with other British fan and debris cone sites (Table 6.8) demonstrates the first phase of aggradation (2000 ^{14}C BP) to correspond with similar activity at four other locations. However, the main aggradation phase at Iron Crag occurs in the Middle Ages which is a little later than most sites which are considered a response to Viking settlement (c. 10-11th Century AD), rather than monastic land use as is argued to be the case at Iron Crag. In both cases the introduction of sheep into the landscape is the catalyst for fan activity, as argued by Pearsall and Pennington (1973) and Harvey *et al.* (1981).

Finally, a comparison of the historical process rates (maximum 11.7 mm a^{-1}) with those measured during the sediment budget study suggest contemporary activity to be far greater, between 46 and 99 mm a^{-1}. However, in qualification of this difference it is pointed out that the palaeo rates are obtained from compacted and reworked sediment, and that the rate of accretion is influenced by the number of dates per unit depth. This suggests that the rates are not easily comparable, but nevertheless demonstrates fan sedimentation at Iron Crag is currently very active.

9.1.4 Contemporary and historical flooding at Raise Beck, Helvellyn.

Investigation of flooding at Raise Beck was undertaken following recent blockage of the A591 road, and the fact that Raise Beck is now a managed mountain torrent, which is an unusual occurrence in the UK. The overall aim was to determine the controls on flooding in this small upland catchment. In this respect three objectives were followed: reconstruction of the 1995 flood event; examination of historical evidence for earlier flood events; and finally, a consideration of the management strategy employed following the 1995 flood.

The flood of the 31st January 1995 is reconstructed in terms of its rainfall characteristics, flow characteristics (velocity and discharge), and geomorphological impact. Rainfall records for the months December 1994 and January 1995 show the Thirlmere catchment was already very wet before the event itself, having received up to 184 % of the long-term monthly average rainfall (section 7.5.1). The catchment wetness index for the week prior to the storm shows the ground to be saturated. Coupled with the frozen ground and snowmelt conditions this would have resulted in significant runoff in response to the storm rainfall. In addition to these antecedent conditions, the storm itself was highly significant, with the 24-hour rainfall total of 163.5 mm equating to a 1 in 80 year event.

Flow reconstructions using palaeohydrological methods, namely boulder competence (Costa, 1983) and channel geometry relations (Jarrett, 1992), provide mean velocities in the range 1.7 to 6.2 m s^{-1} (Table 7.1). Discharge values are computed using the continuity equation, and for the 1995 flood have maximum values between 27 to 74 m^3 s^{-1} (section 7.5.3). The rational method (Mulvaney, 1850) and flood estimation handbook (Houghton-Carr, 1999) catchment parameter method of peak discharge estimation provide values of 5.5 m^3 s^{-1} and 4.2 m^3 s^{-1}, respectively. An order of magnitude difference exists between the palaeohydrological and catchment parameter results. The rainfall-runoff estimates are considered more accurate for the determination of flow conditions during the flood because they make the least assumptions about flow conditions, although the resolution of the rainfall data is relatively coarse (1 hour).

The geomorphological impacts of the 1995 flood are determined from field observations and comparison of pre-flood and post-flood aerial photographs. Reworking of channel deposits, shallow landslides, a major channel avulsion on the basal fan resulting in the blockage of the A591, were the main impacts of the flood event.

Lichenometry and documentary evidence provide the basis for the reconstruction of historical flooding. Lichen-dated boulder deposits are grouped into 5 main flood units (Figure 7.14, Table 7.7). Flood units 1 (1844-1859) and 2 (1860-1880) provide the most widespread evidence of cobble and boulder transport, and comprise the largest deposits in the beck. Preservation of these deposits suggests events since 1880 have not been as geomorphologically effective across the whole of the system as those events prior to 1880. This includes the 1995 flood, which only caused changes in the lower reaches of the channel and on the basal fan. From this evidence it is concluded that high magnitude-low frequency events dominate the operation of this system, suggesting high thresholds for channel and slope adjustment. This finding concurs with the pattern of flood response in other small upland catchments in the UK (McEwen and Werritty, 1988).

Following the 1995 flood the channel was stabilised with riprap boulders and the main flow diverted to Thirlmere reservoir. The fan channel avulsion in 1995 had diverted the flow back to its original flow path to Grasmere. The engineering works provided protection to the base of hillslopes that had failed by shallow landsliding during the flood. A comparison of channel cross section areas occupied by the 1995 flood to those of the newly engineered channel sections shows the latter are considerably smaller than the pre-flood dimensions (Figures 7.17 and 7.18). If a flow of similar magnitude to the 1995 flood were to recur the channel capacity would be exceeded, causing damage to the beck and possible disruption to the A591. Under predicted climate change scenarios the recurrence interval of floods of 1995 magnitude is likely to increase, and enlargement of the current channel is a distinct possibility during future flooding.

9.1.5 Sediment-water flow activity in the Helvellyn and Skiddaw massifs

A survey of torrents, debris flows and mountain streams in the Helvellyn and Skiddaw massifs provides a broader base for the investigation of sediment-water flows in the Lake District. First, the significance and morphometric characteristics of these landforms are investigated. Second, given the variability of geology in the Lake District, its association with sites is considered. Third, the magnitude and frequency aspects of torrent floods and debris flows are investigated. Finally, Iron Crag and Raise Beck are placed within the context of these investigations.

Torrents predominantly occupy first-order tributaries in catchment headwaters, though in some larger torrents higher orders of stream channel occur. The issue of significance is addressed by calculating the percentage area of the massif and catchments occupied by torrents. Percentage aerial contributions for entire massifs do not exceed 2.1%, but by catchment they are more important (up to 100%); smaller hillslope debris flows are even more insignificant in areal terms. Mountain streams are more numerous and larger with regard to channel length and catchment area (Figure 8.8).

Bivariate relationships of three basic statistics (i.e. slope, altitude and aspect) are used to determine preferred sites of torrents. Torrents are characterised by large relative elevation (range 205 to 620 m), a minimum top height of 600 m O.D., and have no preferred orientation. Debris flows have smaller altitudinal ranges (mean 103 m), steep slopes (mean 0.57 m m^{-1}), and again have no preferred orientation (section 8.4.2).

Geological types found in association with sites include Borrowdale volcanics, Skiddaw group slates, and the Iron Crag micro-granite. Torrents show no statistically significant differences in slope, relative elevation or top altitude according to geological type (Table 8.10). However, debris flows do express significant variations in morphometric characteristics according to geology. Debris flows formed on Borrowdale volcanics are steepest, whilst sites on Skiddaw group slates show the greatest relative elevation.

The magnitude of torrent and debris flow events is evaluated using reconstructions of palaeo-velocity. The issue of event frequency is determined using lichenometry. However, in the absence of lichens on debris flow deposits, this approach is limited to torrents. Torrent event velocities are reconstructed using boulder competence relationships, giving values in the range of 3 to 4.5 m s^{-1}. Because of the lack of more precise discharge values detailed conclusions could not be drawn. In terms of event age, torrent flood units cover an age range of 17- 240 years. A collection of flood units at each site allows an estimation of the return interval of high magnitude events, which Tables 8.13 and 8.14 show to vary considerably. The flood units can be used to identify regional flood episodes. Five episodes of regional flooding are identified, four occurring in the Nineteenth Century.

Debris flow velocities and discharges are reconstructed from the super-elevation characteristics of levee deposits. Mean values of velocity are between 0.8 and 1.8

m s^{-1}, and discharges between 0.7 and 4.4 $m^3 s^{-1}$. These are very small in comparison to reported values from other parts of the world. Hence debris flow activity in the Lake District is rather limited. No direct evidence of debris flow frequency is available, but the small numbers of contemporary debris flows (n = 14) over the 250 km^2 study area suggests they are rare events.

Comparing Raise Beck and Iron Crag to the other sites in the Helvellyn and Skiddaw massifs shows them to represent end members of the observed populations. Raise Beck is the largest (133 ha) and highest of torrents (858 m O.D.), with the largest reconstructed flood velocity (6.2 m s^{-1}). Furthermore it has the largest number of site specific flood units (n = 5). In contrast, Iron Crag is amongst the smallest of torrents, having a small catchment area (2.4 ha), the lowest top altitude (600 m O.D.) and the smallest elevation range (205 m). It is, however, geologically unique and has the highest frequency of observed debris flow activity.

9.2 Synthesis of research

This section can be divided into three parts. Firstly, an overall statement of the empirical research, drawing together the findings at the case study sites and the broader regional investigations (section 9.2.1). Secondly, these findings are considered in relation to geomorphological sensitivity and the issue of landform development (section 9.2.2). Thirdly, the findings of this study are compared to other torrent investigations and the gully systems in the nearby Howgill Fells (section 9.2.3).

9.2.1 Overall statement of empirical research

The erosion of torrents in Lake District mountain catchments is currently an active process, though the rate of erosion, the process types involved and dynamics of process in the Skiddaw and Helvellyn massifs vary. Investigations at Iron Crag reveal this torrent to be continually active. The movement of sediment from hillslope zones, through the channel system and onto the basal fan has been monitored. The channel and banks play the most important role in sediment supply and transfer within this system. The movement of sediment in the channel is dominated by fluvial activity, though debris flows have been observed, both in the period of monitoring and from considerations of historical process activity. Raise Beck, by contrast, shows less change. Reconstructions of the January 1995 flood, and a series of historical floods during the Nineteenth Century suggest that the geomorphology of this torrent is governed by large flood events that occur infrequently. The boulder deposits of the 1995 flood suggest fluvial processes, and unlike Iron Crag no evidence of debris flows is found. Debris flow activity over the study region was mainly identified on steep hillslopes, and not in channels, where debris flow levees and lobes tend to be quickly modified by fluvial activity. Relationships between meteorological conditions (rainfall and temperature) and process activity were investigated in most detail at Iron Crag with regard to hillslope colluvium particle size characteristics. Slight differences in trapped sediments associated with freeze-thaw and rainfall conditions were identified, but on the whole meteorological control was difficult to establish at this level of investigation. Evidence of the impact of meteorological events at Iron Crag on the channel, banks, and fan demonstrate greater activity during large (but not rare) rainfall events. In contrast, at Raise Beck a significant geomorphological response only occurs following rare rainfall events (e.g. January 1995). The regional survey of torrents identifies a number of sites (Foul Gill, Tongues Beck, Wintergroove Gill, Rydal Fell, Hoggett Gill) where the evidence of process activity on fans is dominated by old boulder deposits, again indicative of larger magnitude events.

Historical process activity has been considered at all sites. At Iron Crag reconstructions of process activity (fan) over the decadal scale were obtained from a series of aerial photographs, whilst over a millennial scale changes in process type and rate have been determined from an analysis of fan sediments. Results have shown phases of fan aggradation, revegetation and entrenchment in the recent past. Over hundreds of years phases of rapid aggradation in association within climate and land use change have also been identified. Raise Beck, and other torrents in the study region, show similar phases of increased activity punctuated by longer periods of stability or reduced activity. This suggests that most torrents are geomorphological systems that are relatively insensitive to external forcing.

9.2.2 A consideration of sensitivity and landform development

The concept of geomorphological sensitivity was first introduced by Brunsden and Thornes (1979), where it is defined as the ratio of disturbing to resisting forces. Brunsden (2001) states that sensitivity concerns the likelihood that a given change in the controls of a system or the forces applied to the system will produce a sensible, recognisable, sustained response. Harvey (2001) and Werritty and Leys (2001) use this idea to suggest that landforms can react in two ways: they are either robust or responsive. Robust landforms are those that have a capacity to absorb change with only minor adjustment, and ultimately maintain an overall landform assemblage. Werritty and Leys (2001) consider that these adjustments are a function of crossing intrinsic thresholds (Schumm, 1979) within the boundaries of more major (extrinsic) thresholds. Harvey (2001) contends that the small-scale changes are due to effective feedback mechanisms that provide rapid stabilisation after disturbance. In terms of Wolman and Gerson (1978), return to a previous state is a process of 'recovery' that signifies ineffective geomorphological activity. By contrast, a responsive (Werritty and Leys, 2001) or a delicate landform (Harvey, 2001) is one which easily undergoes a fundamental and persistent change in the morphology by crossing an extrinsic threshold. Harvey (2001), following Schumm (1991) and Downs and Gregory (1993), argues that such systems operate near extrinsic thresholds; inability to recover signifies that a 'geomorphologically effective' event has occurred, and the system has expressed sensitivity. Therefore, formative events are a function of both the magnitude and frequency of the process activity and the response of the system to these events.

This qualitative concept is critically evaluated in respect to the Iron Crag and Raise Beck torrent systems. One argument (process argument) is that given a disturbing force (e.g. a known rainfall-runoff event) it is expected that the Iron Crag sediment system will respond more readily than Raise Beck. This is because the resisting forces at Raise Beck are greater, e.g. vegetated side slopes, bedrock and coarse armoured stream bed. In this sense Iron Crag is more sensitive to change. A plot of sediment yield against discharge for both streams would clearly demonstrate this.

However, if sensitivity is interpreted as a recognisable change in form (e.g. a transition from a single to multiple thread stream or a major avulsion) then sensitive systems might only be recognised if such features are preserved in the landscape. In this regard Brunsden and Thornes (1979, p479) state:

"..some areas which typically do not exhibit adjustments to continuous but relatively insignificant perturbing forces over long periods of time preserve the effects of large changes for extremely long periods and may even be dominated by landforms entirely produced by large events...Smaller changes will on the other hand only be registered in very sensitive areas, such as current channels, areas of high drainage density or areas of overland flow. This variation in sensitivity leads to a filtering effect where only the very large events, or the integration through a threshold of many small events, can be preserved in the stratigraphic record. In the insensitive areas the smaller changes do not exceed the barriers. In the sensitive areas they do, but the high mobility means the effects are damped quickly."

Following this argument Iron Crag might be regarded as an insensitive form as it undergoes frequent small changes in sensitive areas (e.g. bank collapses, gravel movement in channels, fan sedimentation and revegetation) but retains its overall form. Raise Beck on the other hand is affected by infrequent large events that give a recognisable and persistent response (e.g. the 1995 flood fan apex avulsion, and large shallow landslide). The danger here is comparing the evidence from the two case studies directly. Using the Iron Crag sediment budget study, this establishes change over short timescales and documents transient forms. The Raise Beck investigation looks at historical change and identifies more persistent forms, and without knowledge of the large events would also be considered geomorphologically insensitive. Hence, as argued by Thomas (2001) what we 'see' in the landscape is critically dependent on the resolution of the investigation. The interpretation of Iron Crag as insensitive, and Raise Beck as sensitive conforms to the arguments of Werritty and Leys (2001, p253) who state:

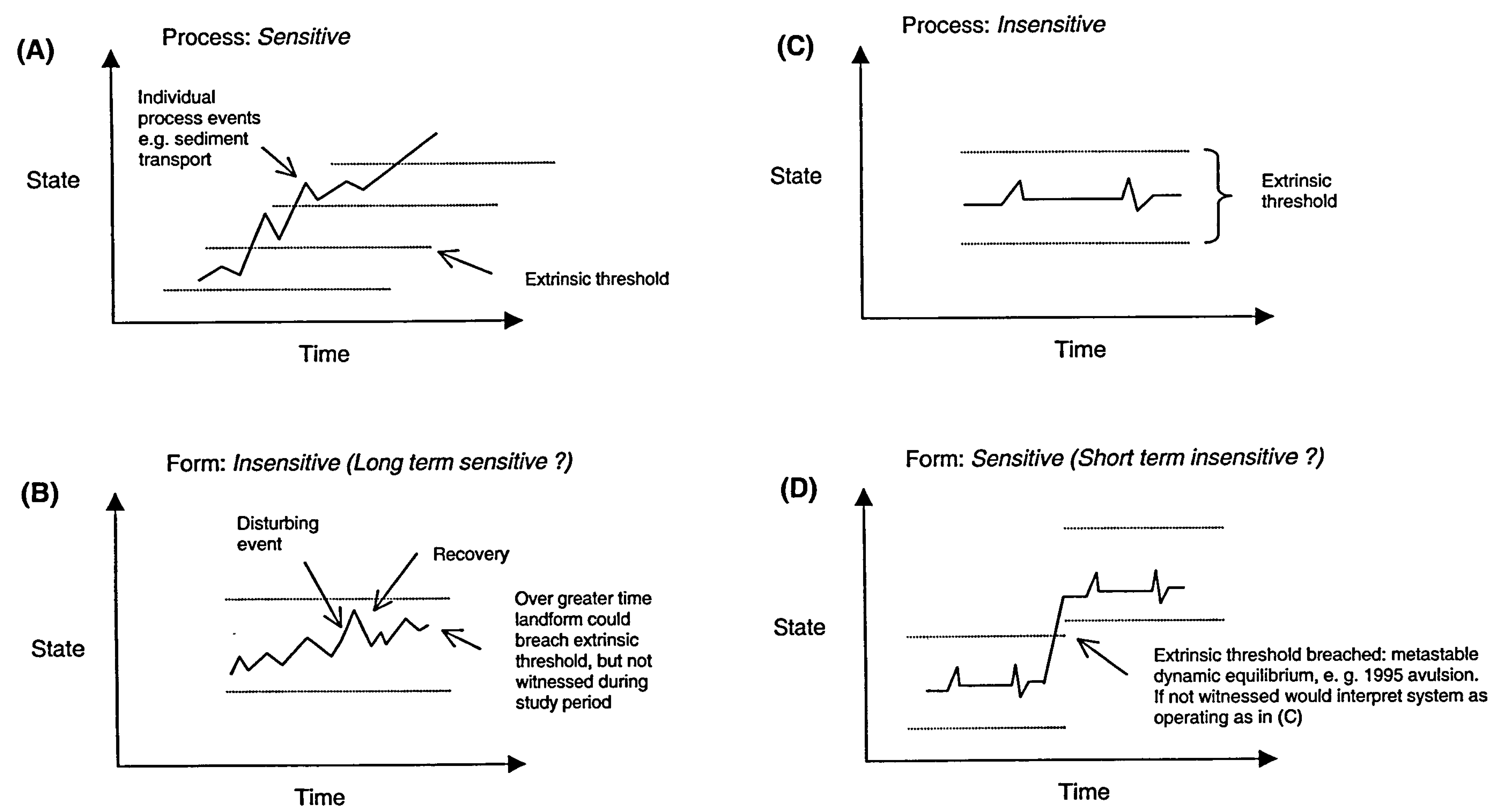
"Whether or not an individual landscape is 'sensitive', thus depends on the magnitude of the change imposed and how close the landform assemblage is to an extrinsic threshold. Only by crossing that threshold does a landform assemblage

display sensitivity to environmental change. It is important to note that 'robust' landscapes are not necessarily stable and can adjust at varying rates in response to environmental change, which only results in an intrinsic threshold being crossed. Thus a meandering river can accelerate or slow down the rate at which it reworks its valley floor in response to changes in flow. But providing the change in flow and/ or sediment supply does not project the river beyond its limiting threshold, the inherent character of the river and valley floor remains unaltered."

This suggests that Iron Crag and Raise Beck can be considered as both sensitive and insensitive, according to whether process or landform assemblage is the basis of the argument, and also according to the temporal resolution of the investigation (see Figure 9.1). Newson (1980) similarly considers geomorphic activity in terms of both work and the effectiveness of these events. Work is identical to the process approach to sensitivity, and effectiveness is akin to form sensitivity. Therefore the concept of geomorphological sensitivity needs further review, most especially with regard to the definition of a significant threshold, as this forms the criterion between a sensitive and insensitive process-form state. Unfortunately uncertainty will remain because such qualitative concepts cannot be easily quantified.

What are the implications of these modes of system operation for the evolution of the Lake District landscape? Both Iron Crag and Raise Beck are active torrent systems, generally operating within the bounds of extrinsic thresholds. The maintenance of dynamic forms for long periods of time means that the landscape only changes slowly. More substantial changes require the crossing of extrinsic thresholds. If the arguments of 'form sensitivity' are accepted, then the high magnitude events required to bring about large changes have been be identified only at Raise Beck. The Brunsden and Thornes (1979) principle of over-adjusted landscapes is perhaps applicable to the Lake District. This principle states that if a harsh environment precedes a gentler one, then subsequent processes will be unable to exceed the barriers of change previously constructed, resulting in the persistence of landforms. Chapter 3 establishes that the current Lake District landscape is the product of past climatic conditions and the associated process activity (periglacial and glacial) and vegetation conditions. Hence torrents are insignificant in the overall evolution of the

Figure 9.1: The alternative interpretations of the conceptual operation of the Iron Crag (A, B) and Raise Beck (C, D) torrent systems.



Lake District landscape, instead they are active facets of current geomorphological activity having only local significance in geomorphological terms.

9.2.3 A comparison of this study to the findings of others

The sediment budget of Iron Crag is a rare example of the use of such an approach in the study of torrent erosion. Two other studies that have attempted similar calculations are Kienholz *et al.* (1991) and Schmidt (1994). Kienholz *et al.* (1991) indicate the dominance of channel-source material in the discharge of sediment from Swiss torrents (60 %), and lesser contributions from banks (23 %) and hillslopes (17 %). This order of zonal contribution is identical to that established at Iron Crag. Furthermore, Iron Crag supplies similar amounts of material from banks (25 %) to the value given for the Swiss torrents, with the greatest difference being the amount of material sourced from hillslopes, being only 5 % at Iron Crag. The findings of Schmidt (1994) also show a dominance of channel sourced material, and a contribution greater than 24 % from hillslopes. As previously argued for Raise Beck, Schmidt (1994) considers the catastrophic flood in the Lainbach catchment to represent a system state of metastable dynamic equilibrium.

Harvey (2001) considers the geomorphological operation of gullies and river channels in the Howgill Fells, Cumbria. A number of comparisons between these hillslope gully systems, and Iron Crag and Raise Beck in the nearby Lake District can be drawn. Overall, the gully systems show a progressive trend towards stabilisation, through decoupling and re-vegetation over timescales of the order of 150 years. The Iron Crag channel is known to have existed in 1823 (Anon, 1823), and more recent observations between 1953 and 2000 show no large change in the hillslope zones of the system. This recovery model is therefore inapplicable to Iron Crag. The maintenance of process activity at Iron Crag possibly reflects the supply of water by springs in the head of the primary zone, the weaker rock type, the active movement of colluvium preventing the formation of soil, and continued disturbance by sheep grazing.

The gullies of the Howgill Fells are considered by Harvey (2001) to reflect robust systems that are only sensitive to high magnitude-low frequency events. Previous discussions could classify Iron Crag as a robust system, in that the overall landform assemblage is maintained following event disturbance. Furthermore, results of the sediment budget show that storm events have noticeable effects on the sediment supply to the fan. However, this did not result in the crossing of an extrinsic threshold. Raise Beck may be considered geomorphologically sensitive to high magnitude events, being unable to recover the previous landform assemblage following the event.

With regard to hillslope processes, Harvey (2001) provides a number of specific observations. Firstly, sediment production is greater during the winter than the summer. At Iron Crag the yields of sediment from wash processes and rockfall, demonstrate similar behaviour through the seasons (explanations are given in Chapter 5). Secondly, mass movement processes are dominant during winter and overland flow during the summer. At Iron Crag wash processes operate throughout the year, and are more significant than rockfall. Third, Harvey (2001) observes that rills are developed and destroyed on the hillslopes during the summer, which is contrary to observations at Iron Crag, where rills were observed year round, with fresh ones developing in response to heavy and prolonged rainfall at any time of the year. Finally, in the Howgills aggradation of cones occurs approximately 30 times a year, and stream floods capable of entraining these occur once every 2- 5 years. At Iron Crag the transfer of sediment from hillslope to the base of hillslopes or the channel occurs regularly, and hence is similar to the Howgill Fells. However, the frequency of channel flows capable of sediment transport is significantly greater than once a year, hence a more rapid transfer of sediment throughout the entire system is experienced. However, it is important to recognise that Harvey (2001) is considering the coupling of hillslopes to larger rivers, whereas Iron Crag is a small system decoupled from the main streams where larger floods occur.

9.3 Preliminary consideration of the likely impacts of land use and climate change on torrent erosion

The 'Environmentally Sensitive Area' scheme is part of the 1986 Agriculture Act, and is applied as a safeguard to areas which are considered of national importance with regard to landscape, wildlife and historical features (Naturenet, 2001). The Lake

District was designated an ESA area in 1992 and one of the objectives was to conserve and enhance the semi-natural vegetation of the fells (ADAS, 1997, LDNPA 1997a). An increase in sheep numbers and stocking densities since the 1970s is considered a threat to the quality and extent of the semi-natural vegetation, particularly heather moorland and montane heath (ADAS, 1997). The LDNPA (1999) maintain that overgrazing by sheep is partly responsible for soil erosion in the Lake District. Farmers participating in the ESA scheme are given incentives to reduce sheep stocking numbers, in the belief that this will mitigate the detrimental effects of overgrazing. Indeed, Evans (1997c) provides examples of sheep induced scars in the Peak District that have re-vegetated under the influence of reduced sheep grazing pressures. Similarly Wilson (1993), and Anderson and Radford (1994), show recovery of vegetation on Kinder Scout under decreased sheep grazing. Therefore if there is a successful subscription to the ESA scheme in the Lake District over a long period of time all other things being equal current sheep scars are likely to re-vegetate. Therefore curtailing land use change by effective land management could reduce the amount of erosion in upland catchments.

Arnell (1996, 1999) and MAFF (2000) present scenarios of future climate change in Britain, based upon results from the UK Hadley Centre transient climate change experiment 1995-1996. Changes are expressed relative to the average 1961-1990 climate. By 2050 it is expected that mean temperatures will have increased in all seasons. Winter temperatures will be 0.8 °C warmer in northern England, and summer temperatures increased 1.2 °C. Year round changes in Cumbria are expected to be 1 to 1.5 °C warmer than the baseline conditions (Figure 9.2). At the annual scale precipitation is likely to increase by over 15% in northern Britain, with noticeable seasonal differences. In Cumbria, autumn and winter months (September to February) will have increases between 5 and 25 %, while spring and summer months (March to August) will experience smaller changes between –5 to 5 % (Figure 9.3).

Arnell (1996) considers the implications of the changing atmospheric conditions on runoff and river channel processes. In northern Britain annual runoff will increase between 5-15 % by 2050. The timing of runoff will change in response to declining

Figure 9.2: Change in seasonal temperature by the 2050s in the UK (Arnell, 1996)

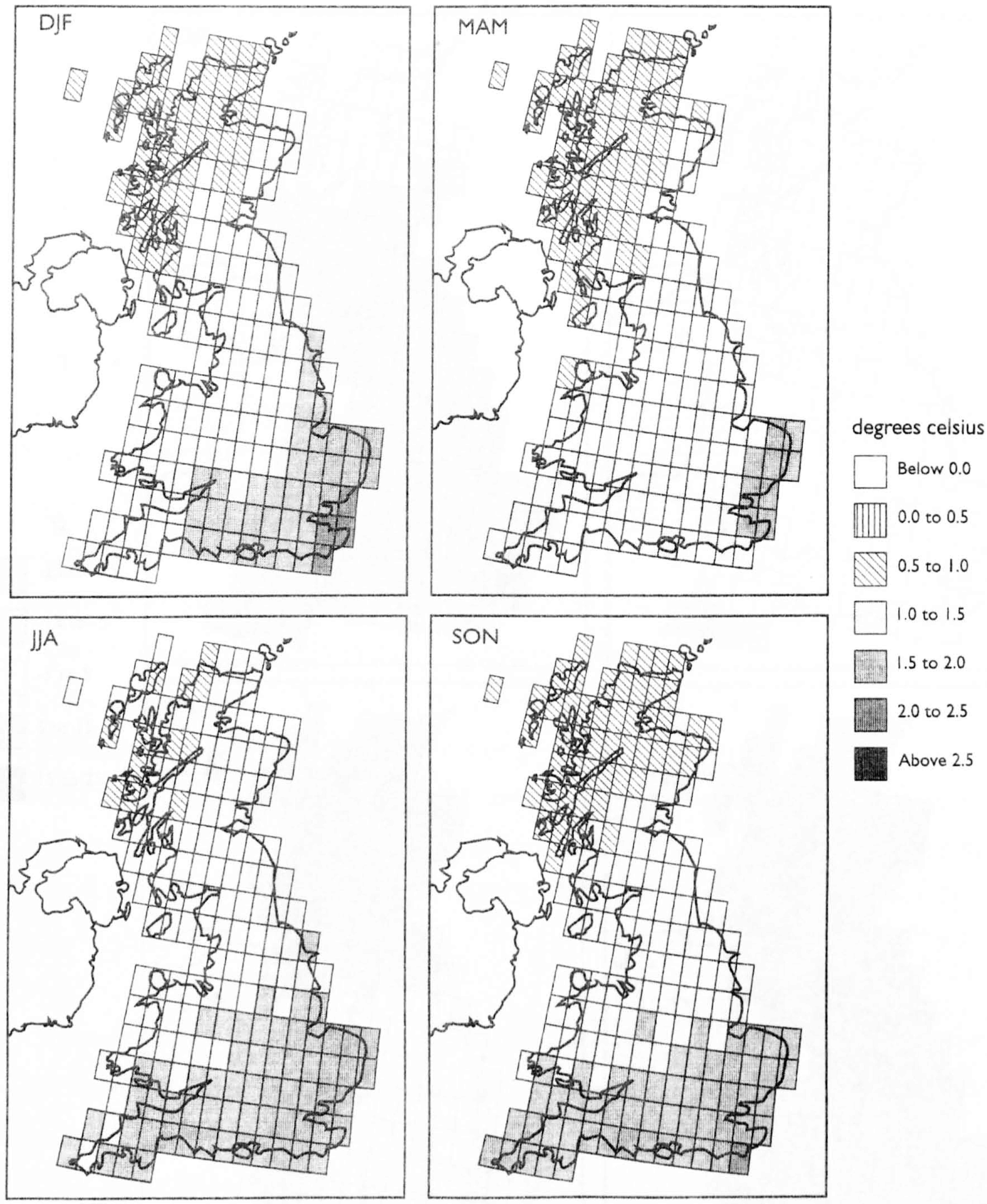
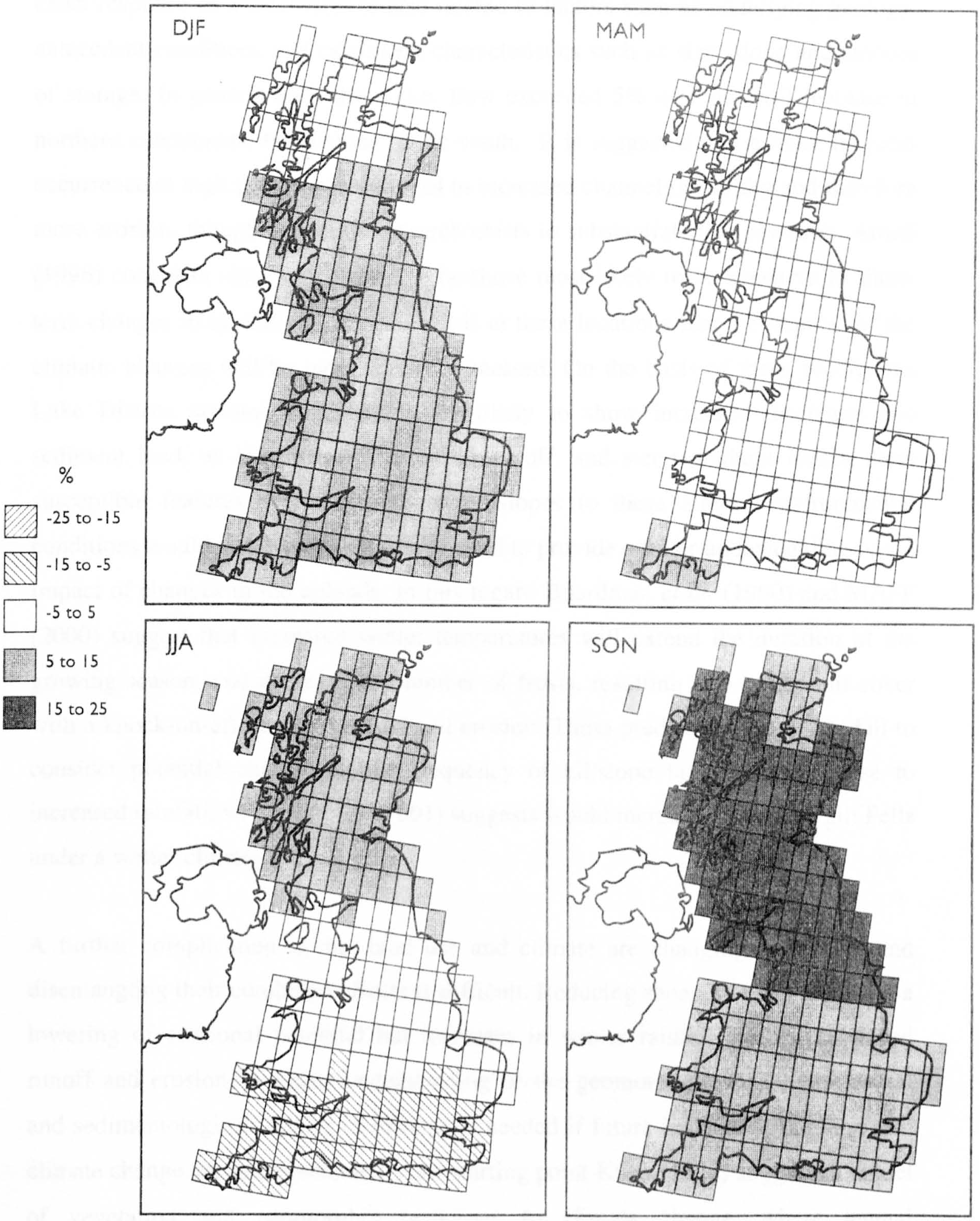


Figure 9.3: Change in seasonal precipitation by the 2050s in the UK (Arnell, 1996)



snowfalls. Spring snowmelt flows will be reduced and winter rainfall will correspondingly increase. The issue of flood occurrence is more complicated as the exact response of a catchment is also related to factors such as underlying geology, antecedent conditions and catchment characteristics such as size, slope and amount of storage. In general high flows (i.e. flow exceeded 5% of time) will increase in northern catchments, but decline in the south. It is suggested that a more frequent occurrence of high peak flows will lead to increased channel instability and therefore more erosion, though very little research exists to substantiate this assertion. Arnell (1996) considers small catchments to be those most likely to be sensitive to short-term changes in rainfall-runoff, hence it is at these locations that the impacts of the climatic changes will be most readily witnessed. On the basis of these predictions Lake District streams and torrents are likely to show increased discharge and sediment load, as their small size, rapid runoff, and steep gradient makes them susceptible features. The response of hillslopes to these altered environmental conditions would also have to be investigated to provide a fuller understanding of the impact of changes in the uplands. In this regard Boardman *et al.* (1990) and MAFF (2000) suggest that increased winter temperatures will extend the duration of the growing season, and decrease the number of frosts, resulting in a better soil cover with a knock-on-effect of decreased soil erosion. These predictions, however, fail to consider potential changes in the frequency of hillslope failures in response to increased rainfall, which Harvey (2001) suggests would increase in the Howgill Fells under a wetter climate.

A further complication is that land use and climate are changing in tandem and disentangling their combined effects is difficult. Reducing sheep numbers points to a lowering of erosional potential but increases in winter rainfall suggest enhanced runoff and erosion. A better understanding of the geomorphological, hydrological and sedimentological aspects of torrents is needed if future impacts of land use and climate change are to be predicted. As a starting point Knox (1972) suggests a model of vegetation and geomorphic responses to climate change, where annual precipitation is between 250 and 1500 mm (Figure 9.4 a). In this an abrupt change in climate, such as an increasingly wet precipitation regime, results in a lagged increase in vegetation cover; a decline in hillslope erosion and an initial spike in sediment yield. Knox (1972) contends that the initial increase in sediment yield reflects the imbalance between the climatic and vegetation regimes. That is to say, larger amounts of precipitation are falling on a surface where the vegetation is unchanged. This simple model of biogeomorphic response can be used to consider the likely impacts of climate and land use change in the Lake District (Figure 9.4 b and c). In Figure 9.4 (b) a scenario of no climatic change (i.e. constant precipitation) but reduction in sheep numbers is shown. The precipitation regime remains constant; the vegetation cover increases but more slowly than when driven by climate. Following Knox (1972), the hillslope erosion potential is considered the inverse of the vegetation cover, and with no change in climate the imbalance of climate and vegetation previously outlined does not exist, and therefore no spike in geomorphic work occurs. Instead the rate of geomorphic work declines slowly. Figure 9.4 (c) considers the combined impact of sheep destocking and a wetter precipitation regime. As in Figure 9.4 (a) the climatic change is represented as a step function. The vegetation response is even more rapid than Figure 9.4 (a) as it is the combined impact of both climatic and land use changes acting in the same direction. The quicker vegetation response is mirrored in the low hillslope potential. The implication of the quicker readjustment is that the window of opportunity for increased geomorphic work (period of climate and vegetation imbalance) is shorter. Therefore the initial erosional spike would be smaller, and/ or shorter in duration. Following the spike the decline to lower levels of geomorphic activity would be quicker than previously experienced. These conceptual models although useful do not consider other process components such as deep-seated landsliding and channel sediment transport processes. Also considerations such as the inter-arrival times of large magnitude floods need to be accounted for as these affect the geomorphological sensitivity of systems. It is possible that as a result of these factors the 'relative geomorphic work' would be more variable through time. To understand these factors a greater knowledge of the operation of torrent systems is required.

9.4 Limitations of the study

9.4.1 Iron Crag sediment budget

Process activity monitored by Gerlach troughs, nets, micro cross-sections, bank profiles, and fan peg array gives location-specific rates. These are extrapolated to

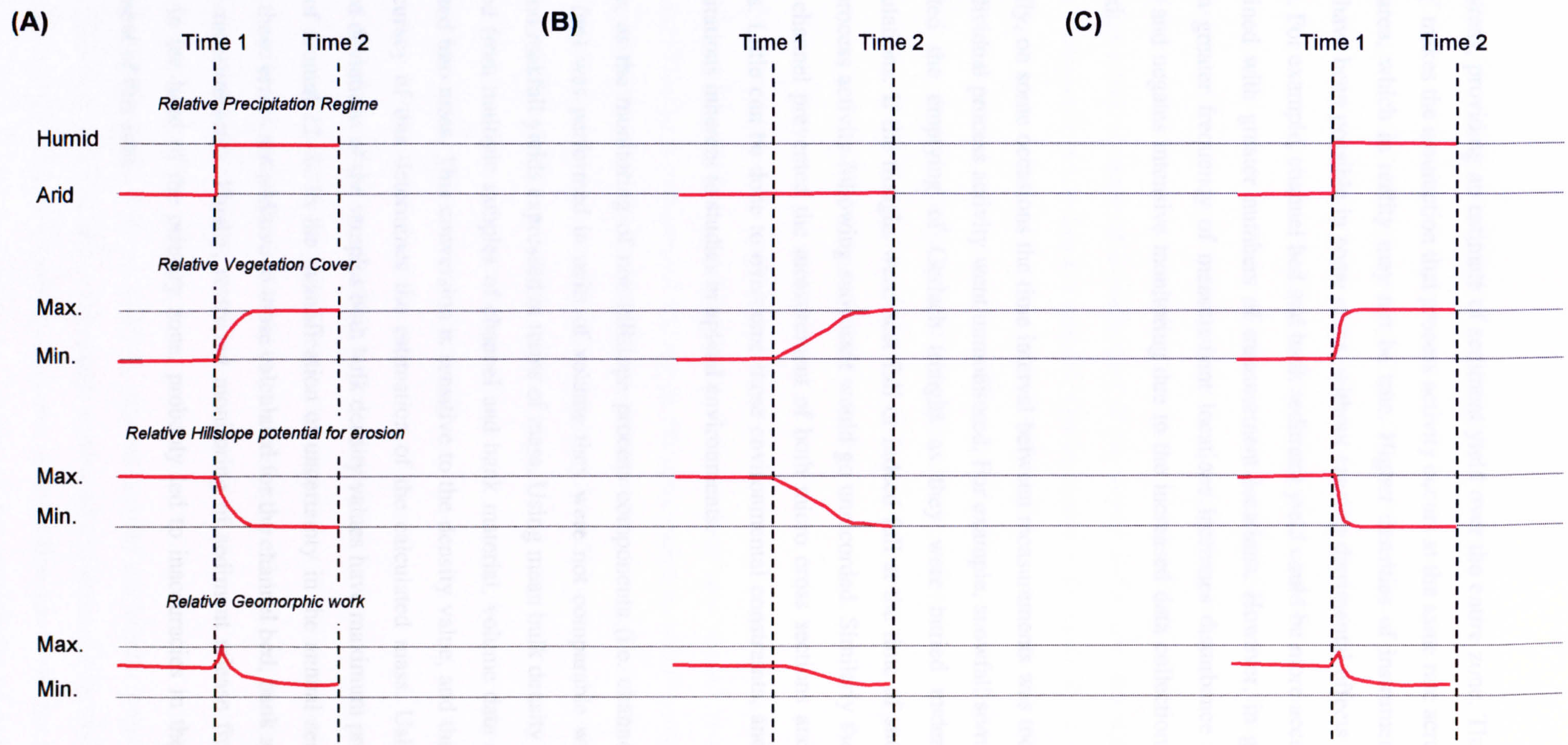


Figure 9.4: Biogeomorophic responses to changing climatic and land use conditions: (A) Original model of Knox (1972); (B) Suggested changes in the Lake District under a scenario of reduced sheep numbers; (C) Suggested changes under a scenario of combined climate change and sheep destocking in the Lake District.

larger areas, providing an estimate of sediment yield over the entire zone. This 'up-scaling' makes the assumption that process activity occurs at the same rate across the entire area, which in reality may not be true. Higher densities of instrumentation would have been possible in some cases, without causing detrimental effects on the system. For example, channel bed and bank sediment yield could be more accurately determined with greater numbers of measurement locations. However, in general terms a greater frequency of measurement locations increases disturbance of the system and negates intensive monitoring due to the increased data collection effort required.

Secondly, on some occasions the time interval between measurements was too long, and individual process activity went unmonitored. For example, snowfall sometimes prevented the emptying of Gerlach troughs as they were buried under deep accumulations. If the troughs were near full or indeed full at the time of snowfall, wash process activity following snowmelt would go unrecorded. Similarly the icing of the channel prevented the measurement of both micro cross sections and bank profiles. Little can be done to overcome these environmental constraints, and these are limitations inherent to studies in upland environments.

Thirdly, as the monitoring of non-hillslope process components (i.e. channel bed, banks, fan) was performed in units of volume they were not comparable with the wash and rockfall yields expressed in terms of mass. Using mean bulk density values obtained from multiple samples of channel and bank material, volume data can be converted into mass. This conversion is sensitive to the density value, and therefore the accuracy of this determines the estimation of the calculated mass. Using the standard deviations of the samples both bulk density values have maximum probable errors of around 12 %. In the quantification of uncertainty in the annual sediment budget these errors are additive to those calculated for the channel bed, bank and fan surface measurements. Finally, restricted monitoring of sediment release from the gullies in the head of the primary zone, probably led to inaccuracies in the wash component of this zone.

9.4.2 Iron Crag contemporary hillslope process sedimentology

The concept of 'dominant process activity' was used to characterise the major process occurring in a measurement interval, thereby allowing an assessment of the impact of process type on particle size characteristics of sediment collected by Gerlach troughs and nets. The results show minimal difference in particle size according to process (Figures 4.11, 4.15 and 4.16) suggesting that deposits are not derived from one dominant process during a measurement interval, or that on steep slopes size selective transport is ineffective. If the former is the case, the dominant process classifications are thus too general. The limitation is therefore in the design of sediment collection and the determination of process activity through reconstruction and not direct observation. The emptying of sediment traps every few weeks was an adequate design for sediment yield determination, but inadequate for process determination. In retrospect the temporal frequency of the emptying of the Gerlach troughs and nets could have been increased.

Secondly, to better test the hypothesised particle size characteristics of sediment, continual sampling of the parent material in each hillslope zone should have been performed. This is because process activity on changing parent material conditions is likely to cause some variability in the signature of process activity. Interestingly the lack of variability in trapped sediments suggests the hillslope source sediments remain relatively constant.

9.4.3 Historical fan process activity at Iron Crag

The number of process 'type' samples is small, providing a limited data set to define the particle size characteristics of sediments associated with different processes. Larger number of samples would better illustrate the variability in particle size characteristics of a given process type.

Secondly, the reconstructions of historical process activity are based on sediments exposed in three pit excavations. This small number of exposures limits evaluation of spatial variability of process activity and rates of deposition across the fan surface (section 6.4.1.2.3, and Figure 6.20). It also limited the availability of sediments suitable for both radiocarbon dating and pollen analysis. Furthermore, the depth of excavations determines the maximum age of sediment exposed. This was limited as it was agreed with the Lake District National Park Authority that only a few small pits would be dug, causing minimal disturbance to the fan. Hence the possibility of digging larger numbers of pits, or indeed trenches, never existed. The depth of pits was controlled by a combination of safety considerations, the difficulty of extracting sediment with spade and bucket, and also flooding below the local water table.

Thirdly, the quality of dating control and hence determination of process rates is constrained by the availability of evidence. The only improvement that could be made is an attempt to maximise the number of datable deposits by increasing the size and depth of exposures. Within the context of the imposed framework, the chronologies presented in Chapter 6 represent the best available reconstructions.

9.4.4 Flooding of the Raise Beck torrent

The major limitation in reconstructing palaeofloods is the necessary application of indirect methods (i.e. palaeohydrology and rainfall runoff calculations) to determine the flow velocity and discharge. The absence of stream gauging records means no check on the calculations can be made. The palaeohydrological equations of Costa (1983) and Jarrett (1992) (Equations 7.1 and 7.8 respectively) were used to determine flow velocity. Discharge was determined from the continuity equation (7.12). A limiting factor of equations 7.1 and 7.8 is their applicability to Raise Beck, given that the power relationships in the equations are based on empirical investigation at other sites, which are known to be of gradients less than Raise Beck. According to Clarke (1996) increasing channel slope reduces the velocity required to transport boulders, and by implication equations based on data from lower gradient streams are likely to overestimate velocities when applied to higher gradient locations. A further difficulty of both equations 7.8 and 7.12 is the need to estimate the geometry of the flood channel. Variations in the estimate of upper flood stage, the extent of modification post flood, and the local variability in channel characteristics are all relevant considerations as they alter the results of the reconstructions.

Rainfall-runoff relationships provided an alternative approach for the determination of peak discharge, but again are limited by their data requirements and assumptions. The accuracy of the rational method is subject to how accurately the value of the runoff coefficient can be determined; the inability of the method to consider changing rainfall and runoff, and the absence of snowmelt contributions to runoff. A more sophisticated rainfall-runoff method presented in the Flood Estimation Handbook (Houghton-Carr, 1999) uses rainfall characteristics of the storm (depth, duration, and profile) and the antecedent conditions. In the calculations where data are unavailable multiple regression equations have to be used to provide approximate values. However, Houghton-Carr (1999) considers these to be unreliable for small catchments. Furthermore the input rainfall data for Raise Beck comes from the Nook rain gauge situated 1 km away from the fan apex of the beck, and at a lower altitude (Table 7.2). Therefore it is possible that the antecedent conditions and storm rainfall are even greater for the Raise Beck catchment, resulting in an underestimation of the true discharge.

9.4.5 Regional assessment of sediment-water flow activity

A problem affecting the analyses in Chapter 8 is the small sample size from which broad trends and characteristics are being sought. However, the maximum size of the population is fixed by the occurrence of torrents and debris flow features in the study area. The restrictive definitions of these features have been rigorously applied, and therefore a large number of steep stream catchments are not included in the sample populations. The only way to increase the sample size in this context is by expanding the study area, which has the implication of potentially increasing the number of controlling variables.

Second, the approach used to determine the importance of torrents (i.e. catchment area contribution to massif and drainage basin areas) is simplistic. More meaningful approaches for assessing the importance of torrents would be a consideration of hazard potential, or the amount of geomorphic work performed. Hazard potential would be of use to local land use planning and flood mitigation. Quantifying the amount of geomorphic work performed by torrents relative to other landscape forms would indicate the contribution of torrents to local landscape denudation.

9.5 Recommendations for further work

Future research benefits from past research in two important ways: improvements to the methodology and techniques in light of the limitations demonstrated in the present work; and the generation of new questions to be investigated. These new developments are, however, still subject to the same constraints of the original study, i.e. National Park regulations, access and feasibility.

1) Develop and test non-intrusive methods for monitoring volumetric change of hillslopes. This would enable detailed monitoring of both spatial and temporal changes without disturbing the process activity, and remove the need for spatial extrapolation of point measurements. The most obvious method is ground based photogrammetry (e.g. Lane *et al.*, 1999, 2000; and Lane 2000).

2) Assess in detail the transport of bed, suspended and solute load in the Iron Crag torrent. By focussing on the channel, more detailed investigation of the most important sediment source can be determined. This will clarify current understanding of channel sediment yield and provide new information on the timing and importance of the main stream load components.

3) Undertake detailed monitoring of sediment delivery to and from gullies in the head of primary hillslope zone. The limited observations to date suggest sediment accumulation is slow, punctuated by episodes of flushing when overland flow from the upper catchment drains into the hillslope zone during prolonged or heavy rainfall. An improved understanding of this would allow better assessment of the role of hillslope zones in sediment supply at Iron Crag. Sediment traps with load cells are a possible approach.

4) The association of rockfall with cold conditions, specifically the occurrence of freeze-thaw cycles, could be investigated further. Following Matsuoka *et al.* (1997) and Matsuoka and Sakai (1999), online monitoring of rock temperature at multiple depths, rock moisture conditions, and joint spacing dynamics would provide further understanding of the role of freeze-thaw processes. The monitoring of yields could be improved by observing the breakdown of painted

surfaces, and increasing the number of nets and the frequency with which they are emptied. Nets could also be made more rigid, with larger lips to reduce the amount of rock bounce out.

5) Investigate processes controlling particle size distribution of source and eroded sediments. This could be achieved by conducting more detailed field monitoring, whereby trapped and baseline sediments are collected following every meteorological event. Alternatively, laboratory simulation with even greater control would enable different environmental conditions could be introduced, e.g. thermal changes and rainfall simulation.

6) If permission were granted, a larger scale excavation of the Iron Crag fan would provide the opportunity to develop the understanding of process activity and chronology. Of particular importance would be the opening of a trench to examine the lateral extent of the various sedimentary units and palaeosols.

7) The investigation of process activity and chronology of other fans and debris cones in the Lake District would provide a context for the Iron Crag investigations. This would be useful in establishing whether fans respond to local, regional or national changes in climate and land use, thereby adding to the growing number of such reconstructions in the UK.

8) The construction of a weir for the continuous measurement of flow in mountain streams/ torrents would start a record of flow which so far does not exist in these steep drainage features in the Lake District. This information in time would allow questions of event magnitude and frequency to be investigated. Furthermore, if accompanying measurements of sediment transport were also made, like those conducted by Billi *et al.* (1995), issues of sediment transport relationships and sediment yield could be investigated. This information, whilst of academic interest, would also be valuable to North West Water, as it would assist in decisions of flood defence, water supply, and rates of sedimentation in reservoirs.

9) To test and develop the chronology of historical flood episodes in the Lake District, further reconstructions from lichen-covered fluvial deposits are required. These deposits, hitherto neglected, exist in the regional study massifs and other areas of the Lake District. An improved chronology, based on many more sites, would assist in the evaluation of flood magnitude and frequency.

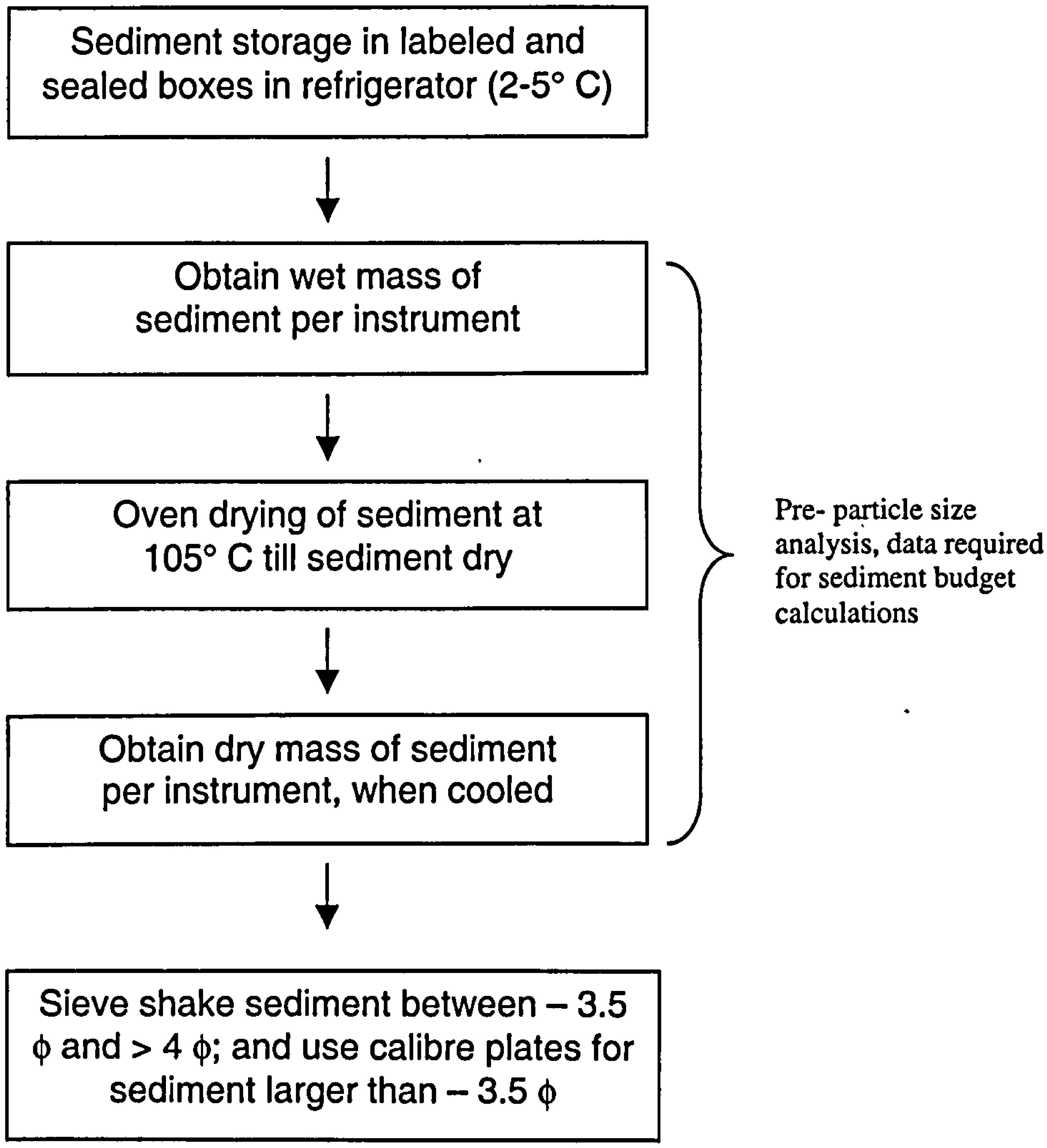
10) A final issue would be to further investigate the sensitivity of torrent erosion in the Lake District, in relation to land use change and predicted future climate change.

APPENDIX 4.1

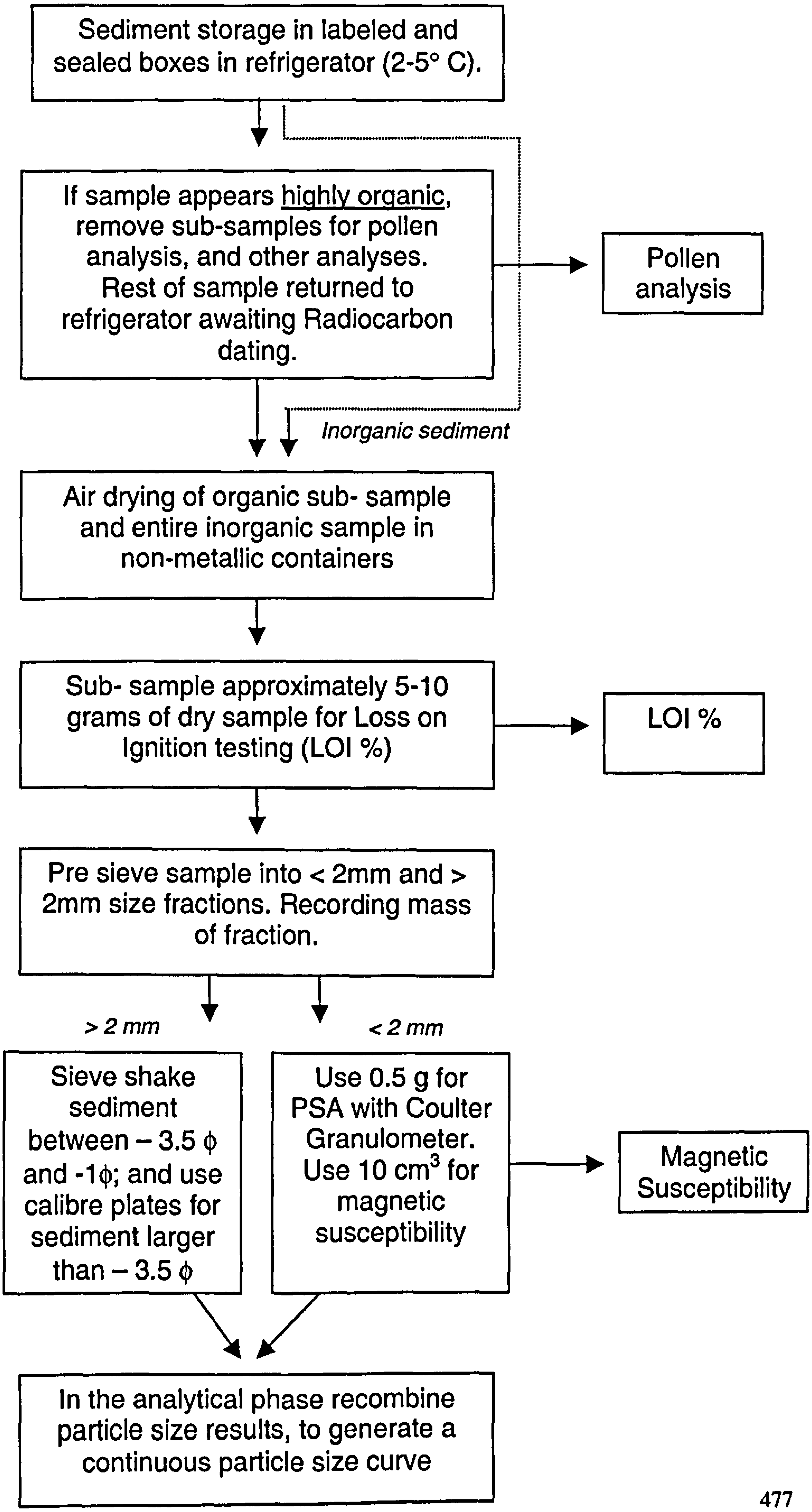
PARTICLE SIZE ANALYSIS LABORATORY ROUTINES FOR SEDIMENTS COLLECTED AT IRON CRAG

1. Trapped sediments (Gerlach troughs and nets)
2. Pit sediments
3. March 1998 'type' sediments
4. Sieve and calibre plate methods
5. Coulter granulometer methods

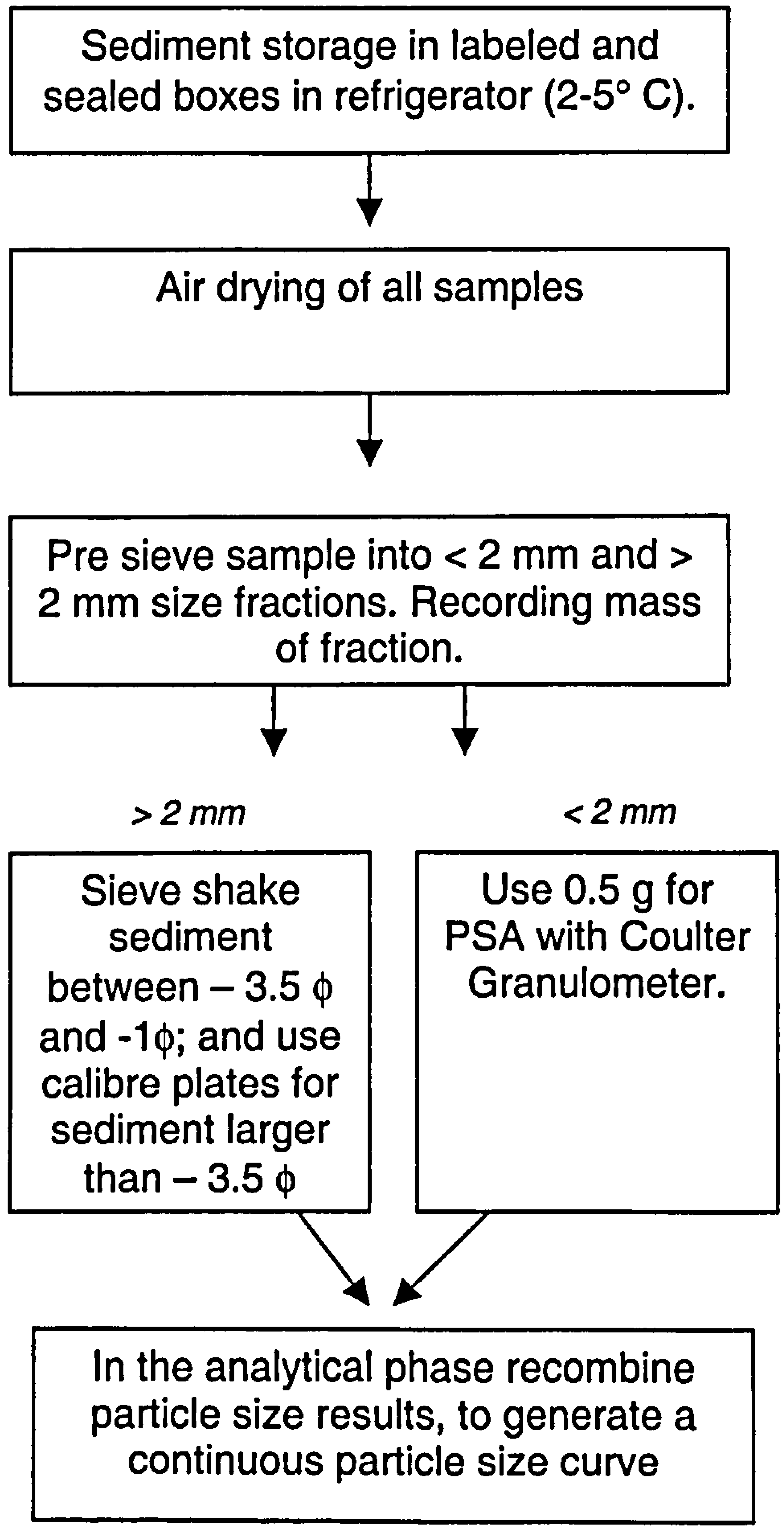
Appendix 4.1-1: Laboratory routine for sediment collected by instruments during the Sediment budget monitoring period



Appendix 4.1-2: Laboratory routine for sediment extracted from horizons in pits dug in basal fan deposit



Appendix 4.1-3: Laboratory routine for sediment collected in March 1998 process deposits.



Appendix 4.1-4: Method of particle size analysis, using sieves and calibre plates. (Derived from Gale and Hoare, 1991).

1. Measure the total mass of the sample in a tared tray, using coarse (0.5g) or fine interval balance (0.01g) according to the sample size.
2. Using a stiff brush and/ or knife clean finer sediment off larger clasts. Add this material to the remainder of the sample.
3. Pre-sieve the entire sample through a 16mm (-4 ϕ) sieve into a receiving pan. All material coarser than 16mm should be placed in a tray for measurement with calibre plates. Calibre plates are metal plates with square apertures of specific phi sizes, and are used to sort large clasts that are too big to be separated by sieving.
4. If any of the < 16 mm sediment in the collecting pan is aggregated it is broken down with a mortar and pestle. This is done using a gentle up and down motion, as a grinding motion would destroy individual particles.
5. The entire < 16 mm sediment is placed in a stack of sieves, from coarsest down to the finest at half phi intervals, with a receiving pan at the base. Having placed the lid on the sieve stack and clamped it firmly to the shaker, sieving proceeds for between 5 to 10 minutes. The length of the time required varies according to the amount of fines in a sample and the overall size of the sample.
6. Step five is repeated if the amount of sediment in the original sample is too great to be passed through the sieves in one run. Then the results are amalgamated. Also in the case of the sediment collected by the instruments, the phi range was too large to allow all sieves to be clamped down as one stack. Therefore 2 stacks were produced, i.e. $-3.5\ \phi$ to $-0\ \phi$; and $0.5\ \phi$ to $> 4\phi$. Here the sediment passing $-0\ \phi$ into the receiving pan is poured into the second finer sieve set.
7. All sediment from steps five and six, is weighed per sieve, from coarser to finest. First the contents of the sieve are tipped onto a clean sheet of paper. Any particles trapped in the sieve mesh are dislodged with a sieve brush (coarser sieves only) and/ or tapping. Second, the sediment on the paper is transferred into a tared clean sample tray and the mass is written onto a pro-forma record sheet. The sediment is discarded and the procedure is repeated for successively finer sieves.
8. The clasts separated at step three are now measured using the calibre plates. The clast is successively passed through the apertures until it comes to the aperture it will not pass through. The clast is then placed on a sheet of paper with this aperture diameter. Once every clast has been sorted in this way, the mass of clasts coarser than each aperture are weighed and recorded on the pro-forma record sheets.
9. Once sieves and other instruments are cleaned this process is repeated for the next sample.

Appendix 5.1- 5: Coulter granulometer particle size sample preparation method. Derived from information sheet (Department of Geography, University of Durham).

1. Place 0.5g of <2mm sediment into a 50 ml tube
2. Add 10 ml of distilled water to wash all the sediment to base of the tube
3. Add 10 ml of 20% hydrogen peroxide. This breaks down organic material which can block up the Coulter granulometer and also alter the results.
4. Cover the open tubes with aluminum foil and place in water bath for two hours
5. After two hours the samples should are checked to check if any organic matter remains. Larger strands of fibrous matter can be removed carefully with a glass rod. If organic matter remains stages 3 and 4 should be repeated. This cycle continues until all organic matter is dissolved
6. Centrifuge samples at 4000 rpm for four minutes and decant half of the liquid off. Top up with distilled water, centrifuge and decant again.
7. Add 20 ml of distilled water, followed by 2-5 ml of Sodium hexametaphosphate solution. The latter is a wetting agent that discourages aggregation of particles.
8. Analyse the sample in the Coulter granulometer.

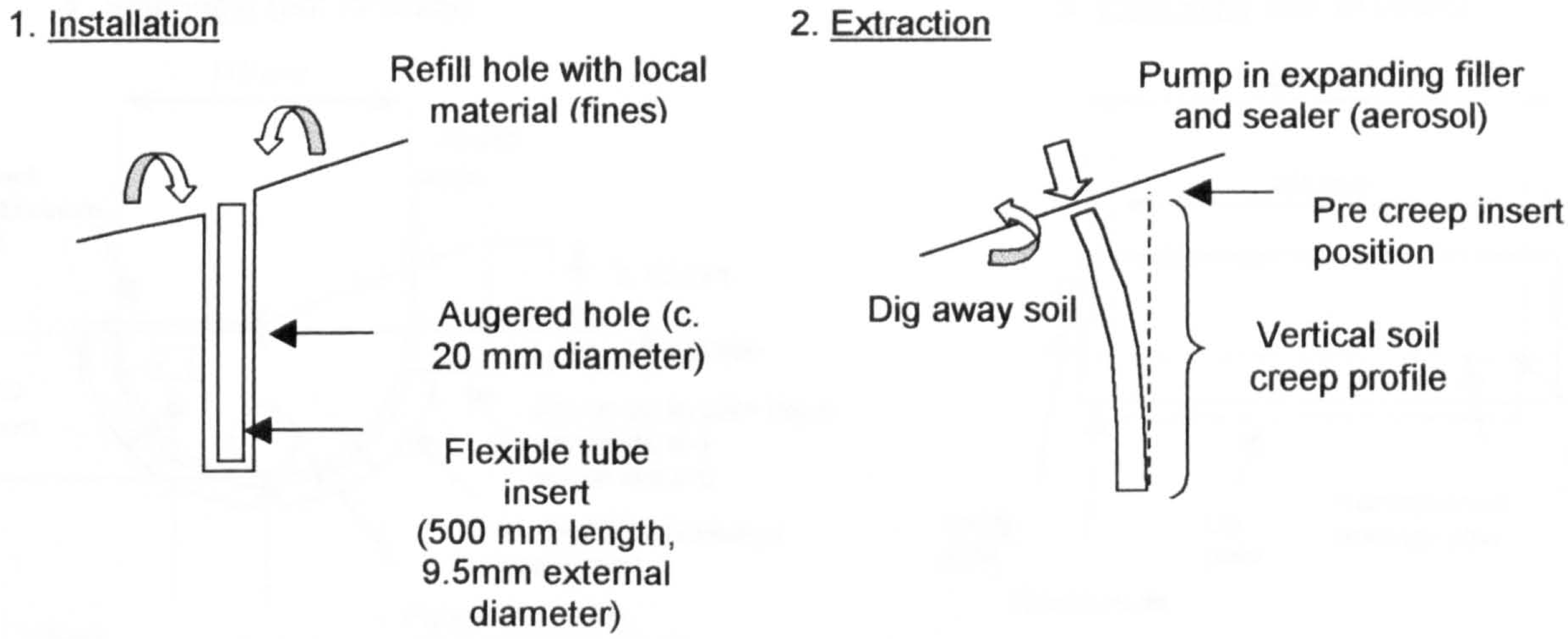
APPENDIX 5.1

DESIGN AND APPLICATION OF INSTRUMENTATION AND SURVEY TECHNIQUES AT IRON CRAG

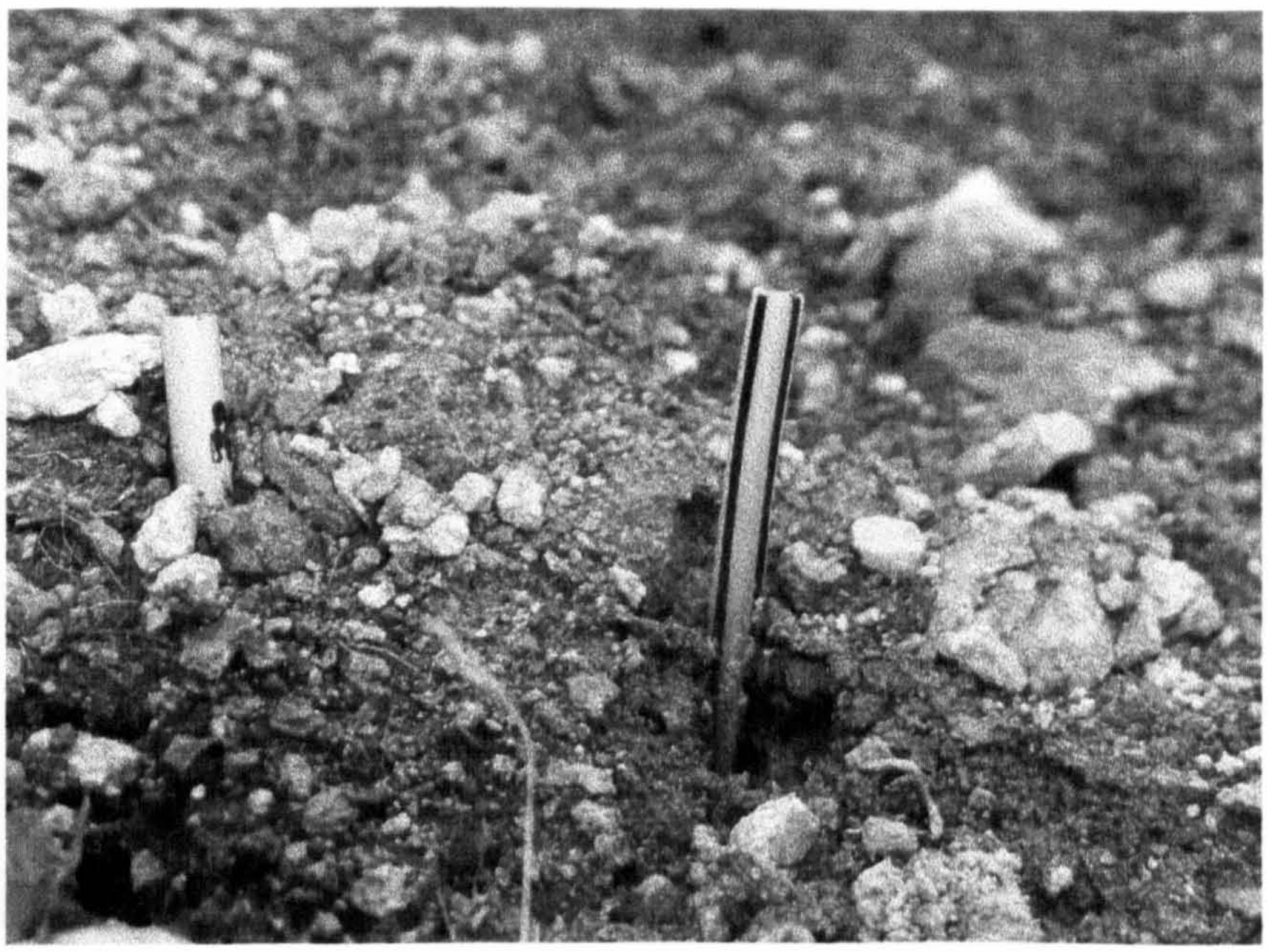
1. Creep tubes
2. Gerlach troughs
3. Draining Gerlach trough
4. Gerlach trough catchment area (field)
5. Nets
6. Rockfall inventory from base photographs
7. Rill geometry
8. Slope erosion pins
9. Channel bank erosion pins
10. Bank profiles
11. Macro cross sections
12. Micro cross sections
13. Scour chains
14. Bedload tracer
15. Bedload initial motion timing loggers
16. Channel planform surveys
17. Suspended sediment sampling and discharge measurements
18. Fan peg array
19. Fan deposit surveys
20. Rain gauge
21. Temperature logging

1. Creep tubes

Design Drawing (not to scale)



Photograph



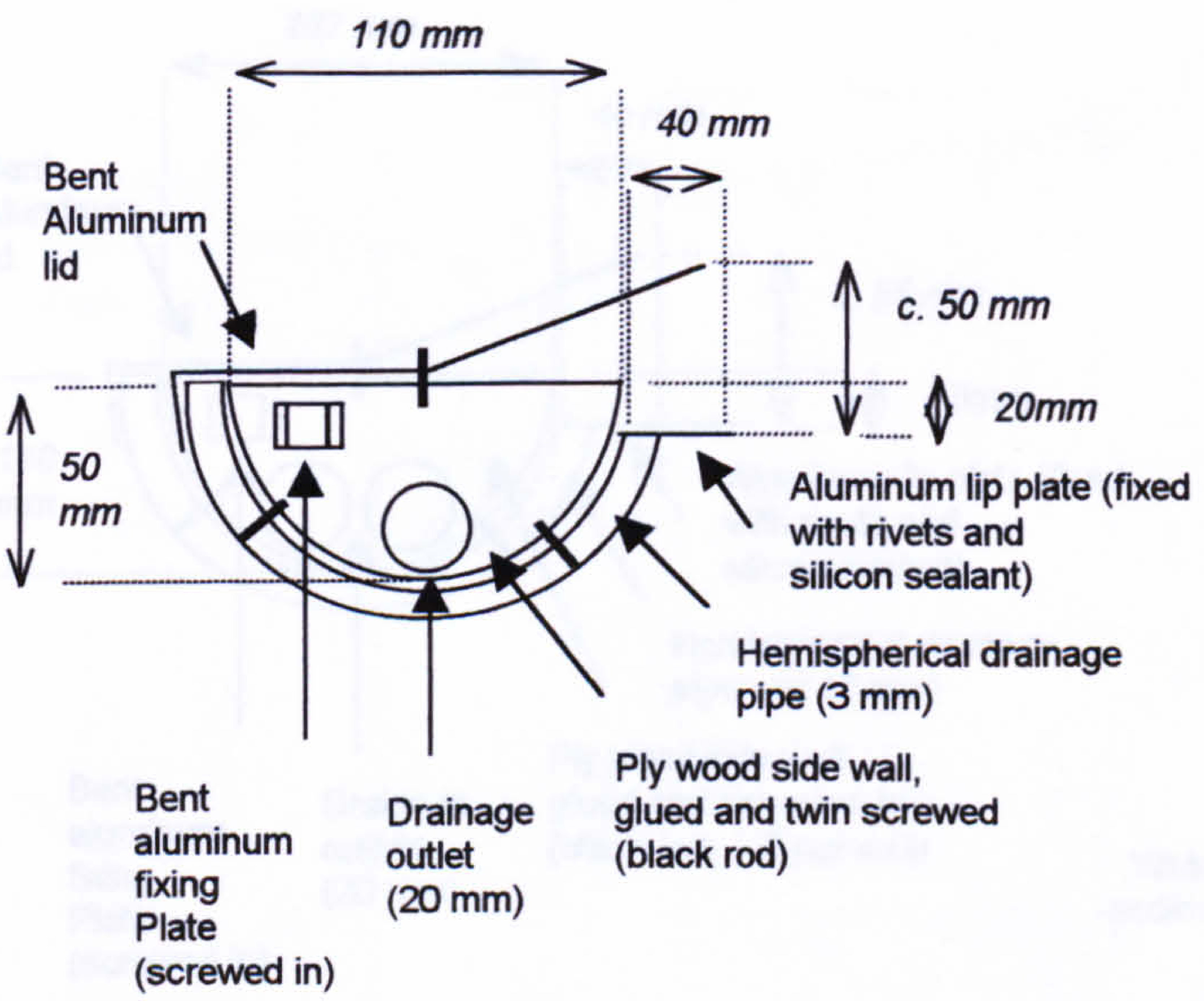
Measurement technique

1. Insert tube into vertical hole, and refill with local material. Label location with cane marker.
2. Leave for extended period of time (minimum c. 6 months)
3. Locate tube insert, inject liquid foam into the tube and allow to set (warm temperatures required c. > 10 ° C).
4. Dig out tube, and trace curvature onto laminated graph paper. This is done in the field in case the foam cracks.

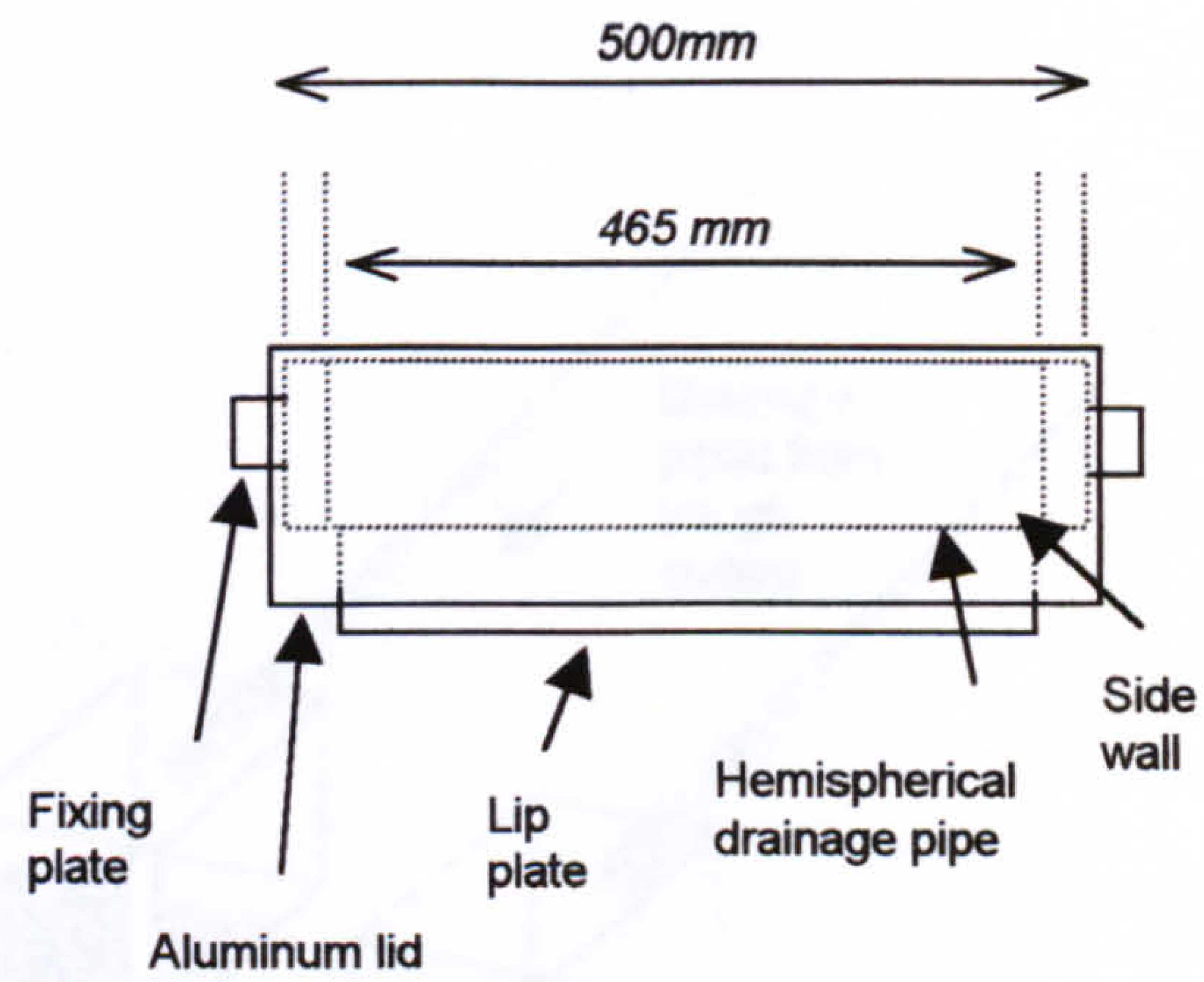
2. Gerlach troughs

Design Drawing

1. Side view (not to scale)



2. Plan view (not to scale)



Photograph

Here the lid is removed, to extract the collected sediment. Also the overflow tube and bottle are unattached.

Sediment is seen to be resting on the lip plate

Capacity: 0.022 m^3

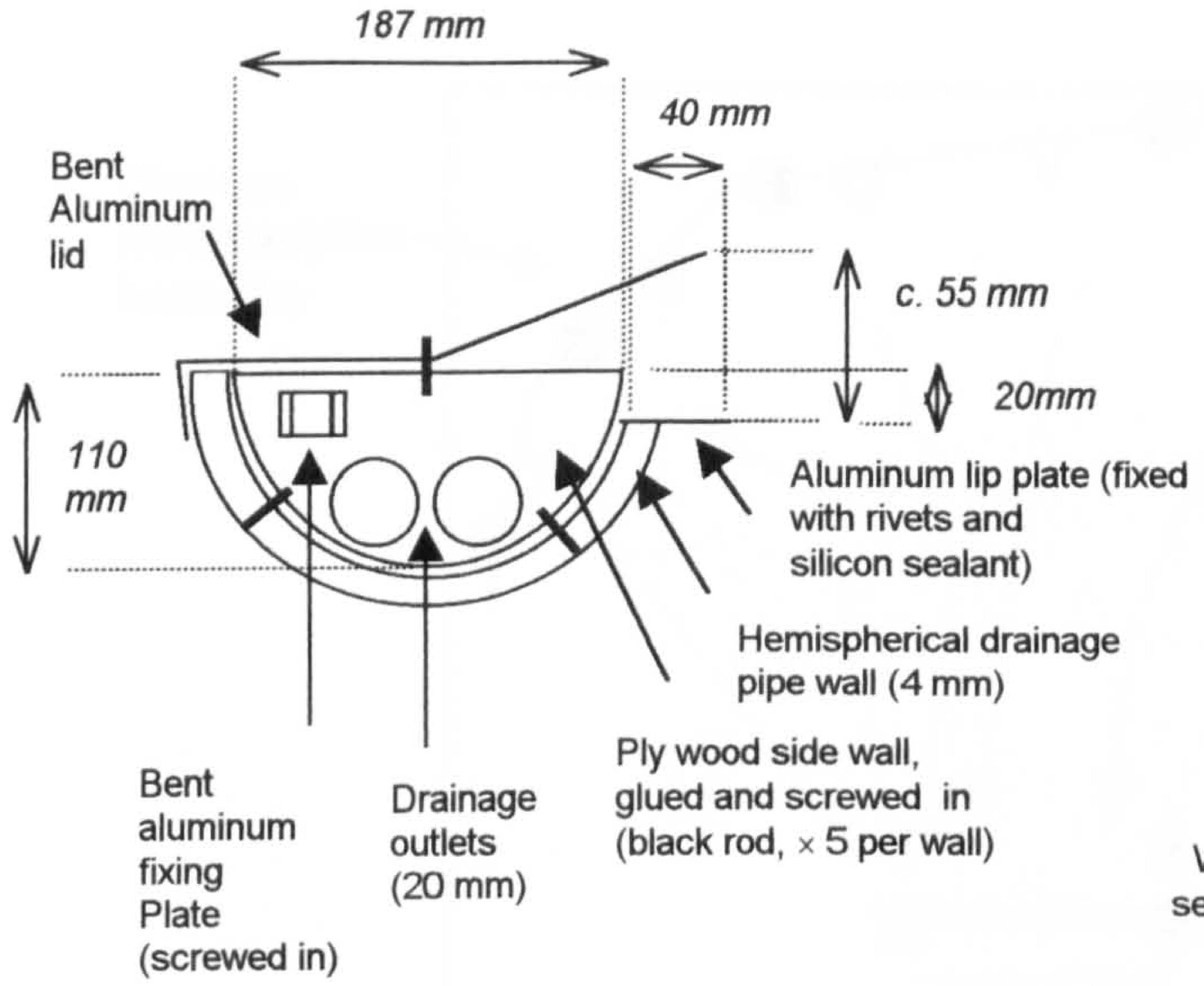
Measurement technique

1. The Gerlach trough lip plate is placed flush with the hillslope surface. It is fixed to slope with pins and grip ties. The overflow tube and bottle are attached.
2. Emptying the trough is performed by lifting the front of the trough away from hillslope to isolate the collected sediment. Unscrew the lid. Sediment is scraped out with a trowel into a labeled sample bag(s). When frozen sediment blocks had to be gently levered out. Overflow bottles were emptied, but the sediment was only found in small quantities.
3. Reset the Gerlach trough for the next measurement interval.

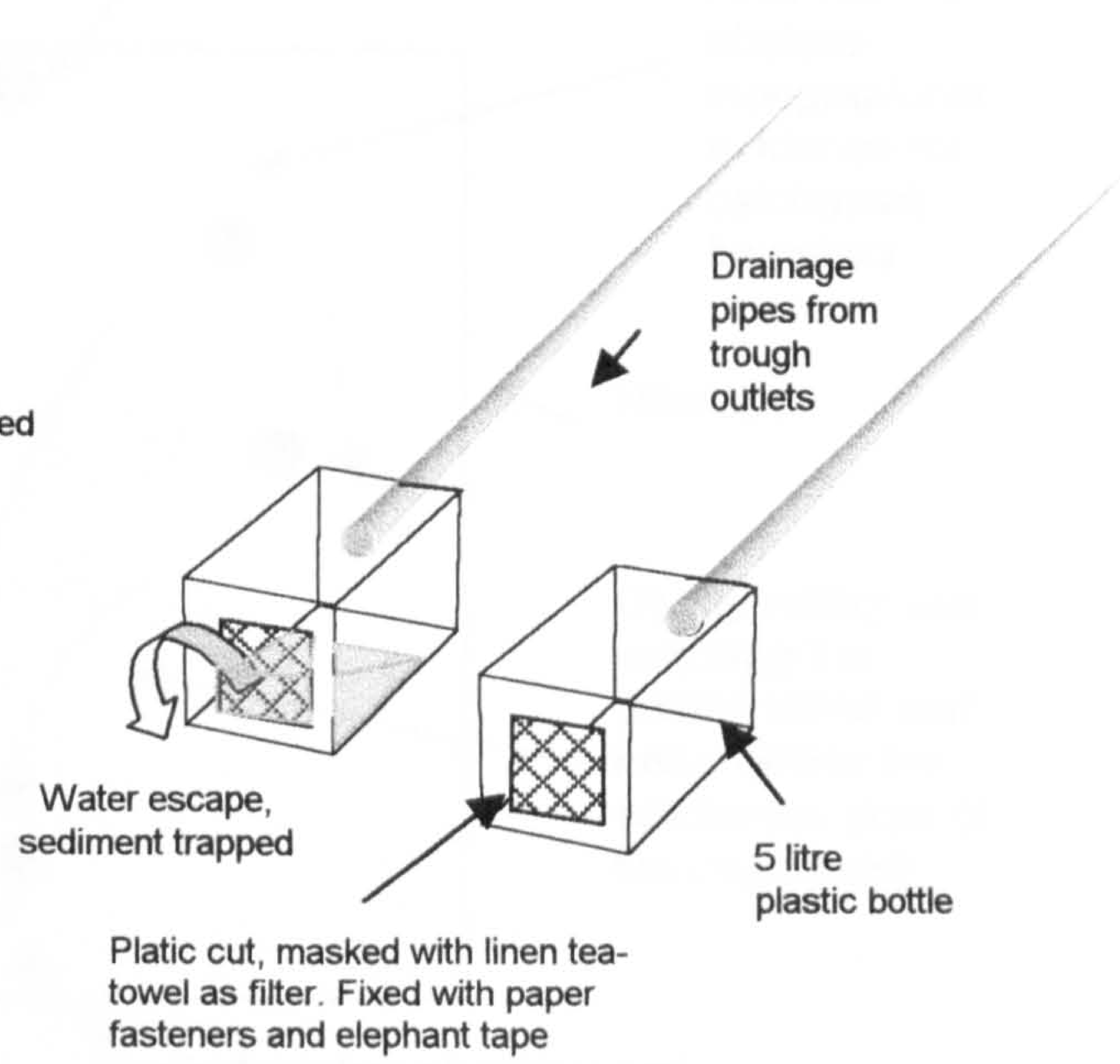
3. Draining Gerlach trough

Design Drawing

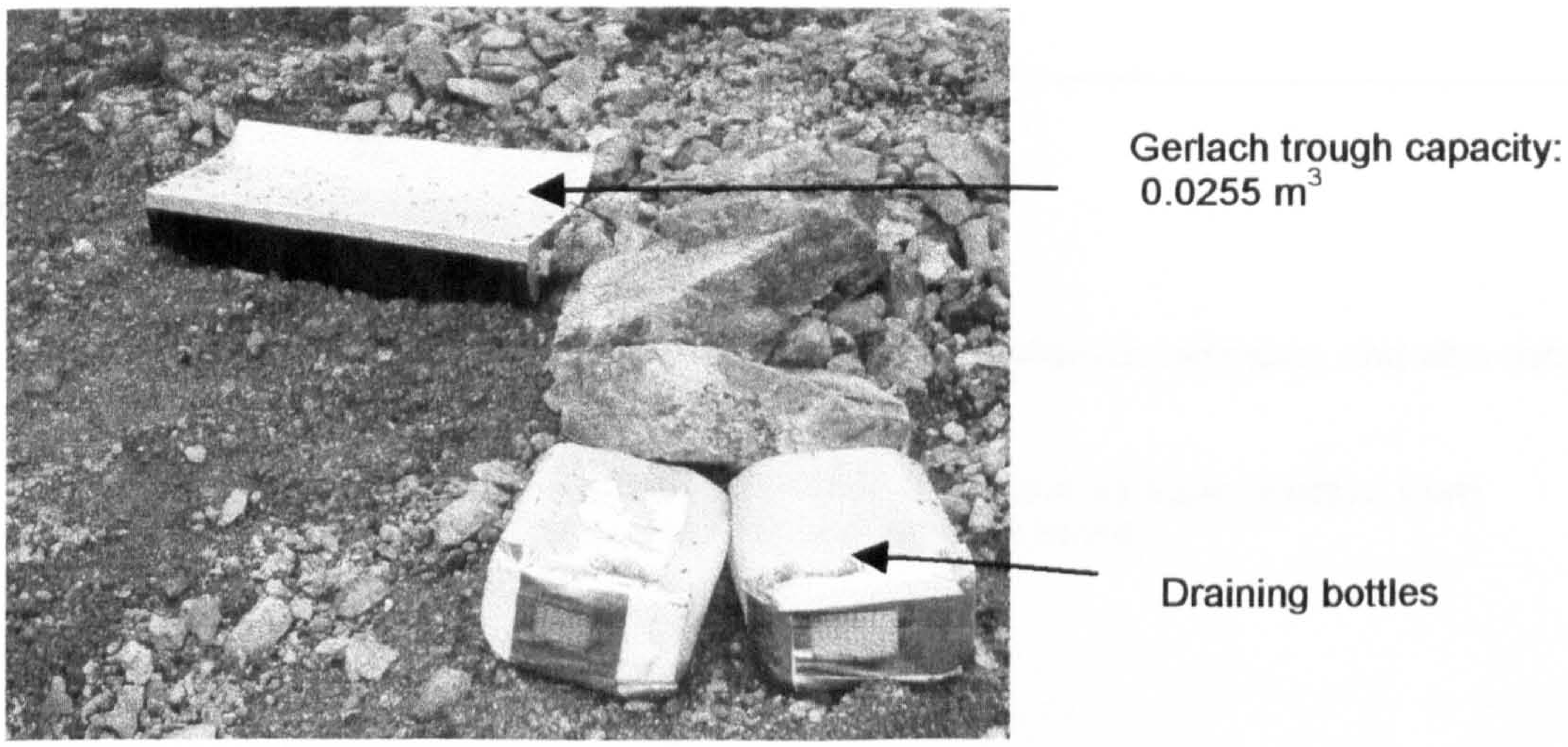
1. Side view (not to scale)



2. Draining bottles (not to scale)



Photograph

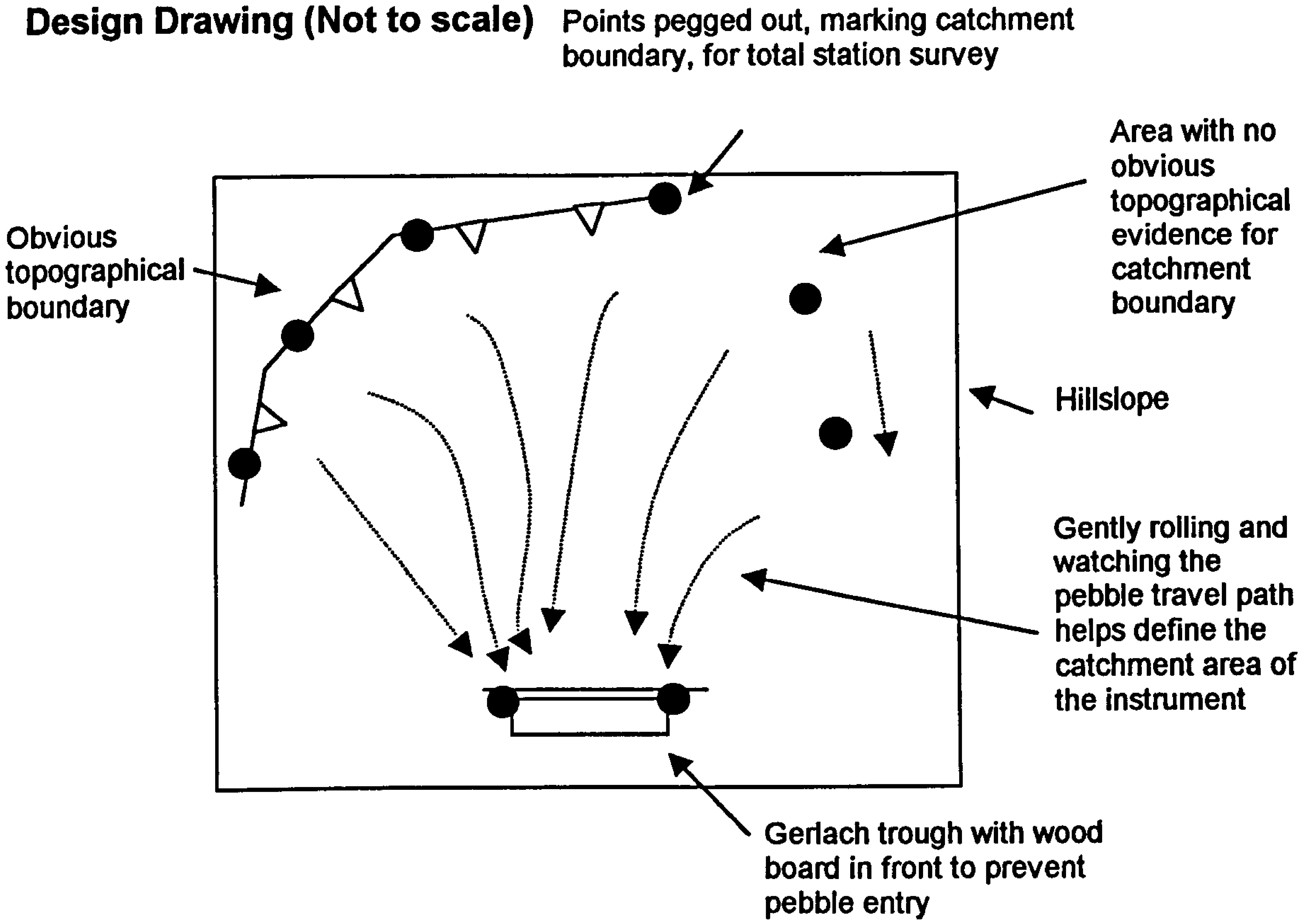


Measurement technique

1. The Gerlach trough lip plate is placed flush with the base of rill. It is fixed to slope with pins and grip ties. The overflow tubes and bottles are attached and weighted down.
2. Emptying the trough is performed by lifting the front of trough away from rill to isolate the collected sediment. Unscrew the lid. Sediment is scraped out with a trowel into a labeled sample bag(s). Bottles are also scraped and washed out into bags.
3. Reset the Gerlach trough for the next measurement interval.

4. Gerlach trough catchment area (field)

Design Drawing (Not to scale)

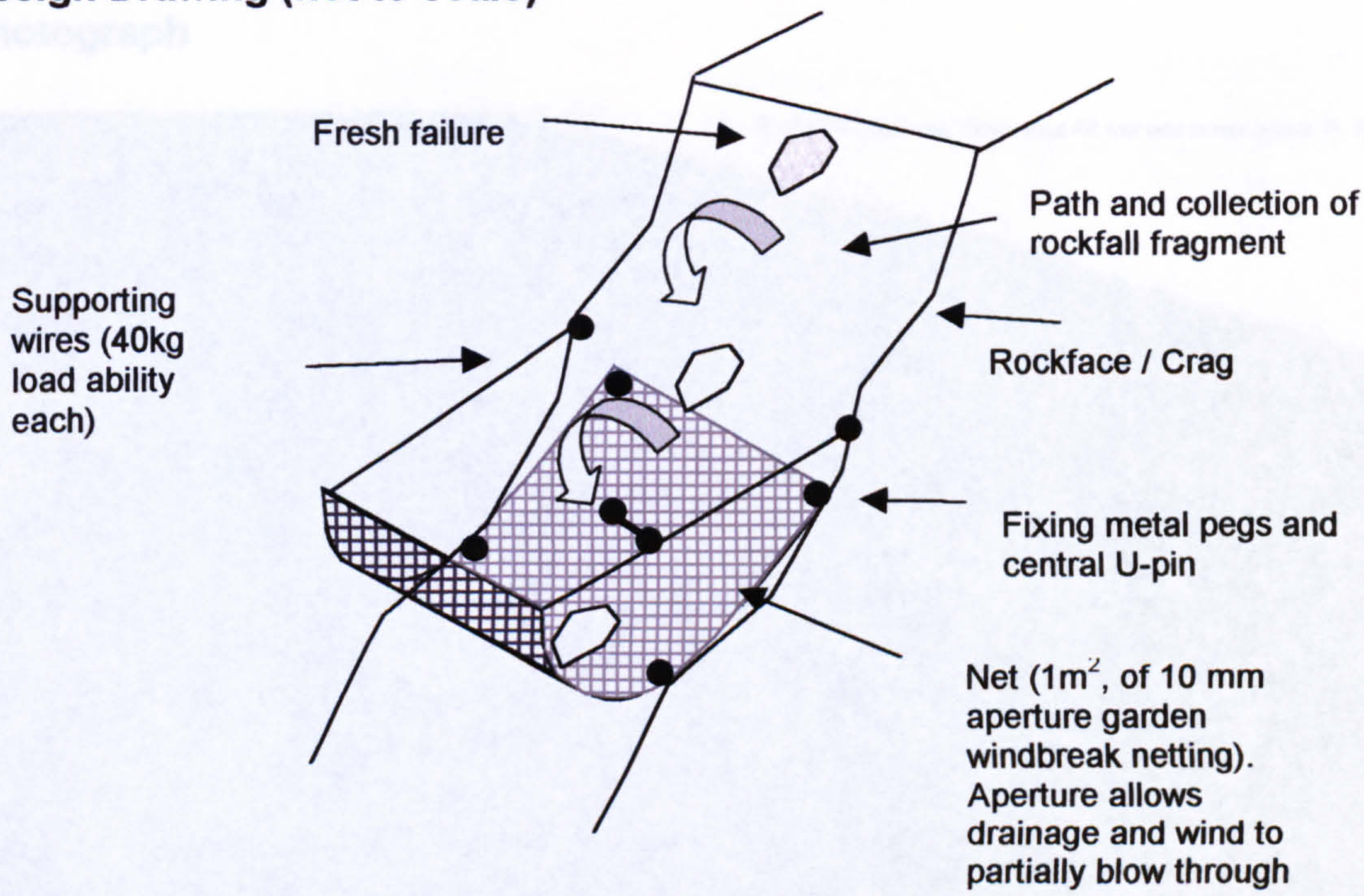


Measurement technique

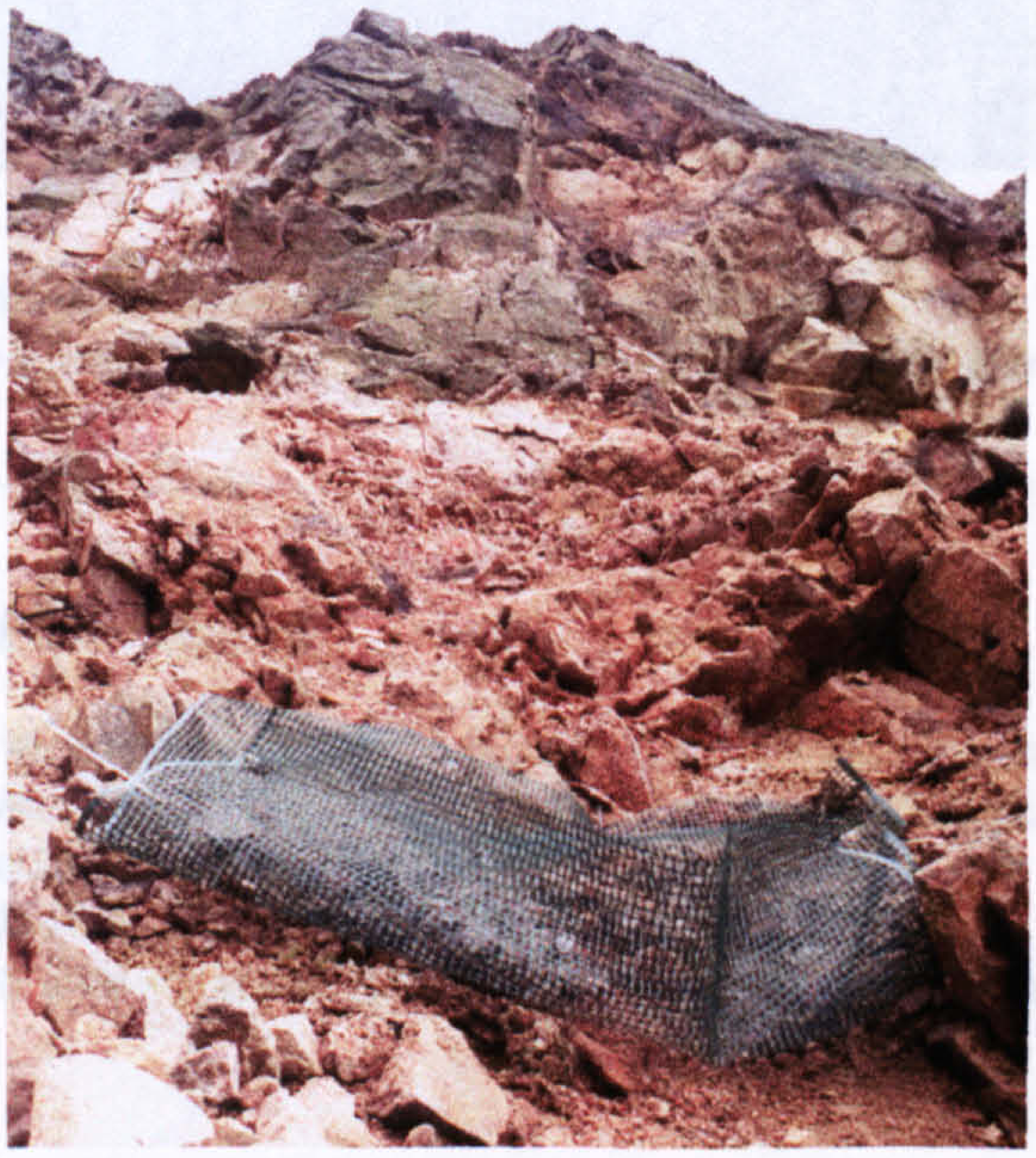
1. Mark out the catchment boundary where topographic evidence indicates, and also using the 'rolling pebble' technique.
2. Survey the marker peg locations with the total station.
3. Where this technique is not possible, catchment areas can be approximated from photographs. This is most relevant to nets beneath rock faces.

5. Nets

Design Drawing (not to scale)



Photograph



Measurement technique

1. If the collected fragments are small in volume, all the material is bagged and returned to the laboratory.
2. However, if the net is full it is impractical to collect all the rockfall deposit. All fragments are weighed in the field with spring balances A sub sample is returned to the laboratory for drying and particle size analysis.
3. Check net fixings, and repair them if necessary

6. Rockfall inventory from base photographs

Photograph

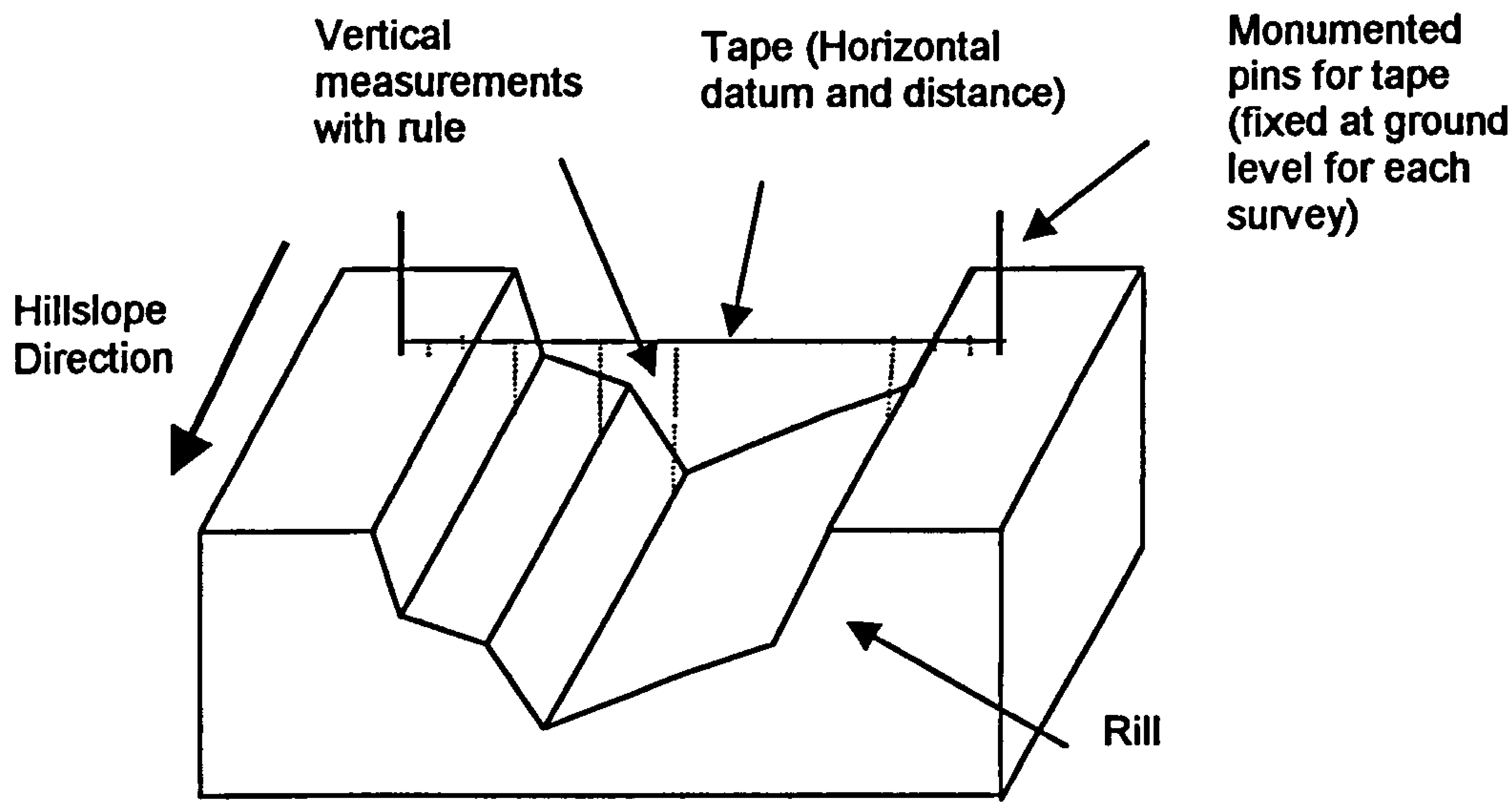
An example of the base photographs, e.g. the top of 'Iron Crag' on the left bank side of the Primary hillslope zone . All the originals are in colour, laminated, and A4 size.

Measurement technique

1. Stand in the location where the base photograph was taken. Compare the base photograph with the rockface in question. Identify and sketch the size and location of any changes onto the acetate overlay
2. Repeat for all photograph locations.
3. N.B. This can only be undertaken in good visibility conditions and when there is no snow cover.

7. Rill geometry

Design Drawing (not to scale)

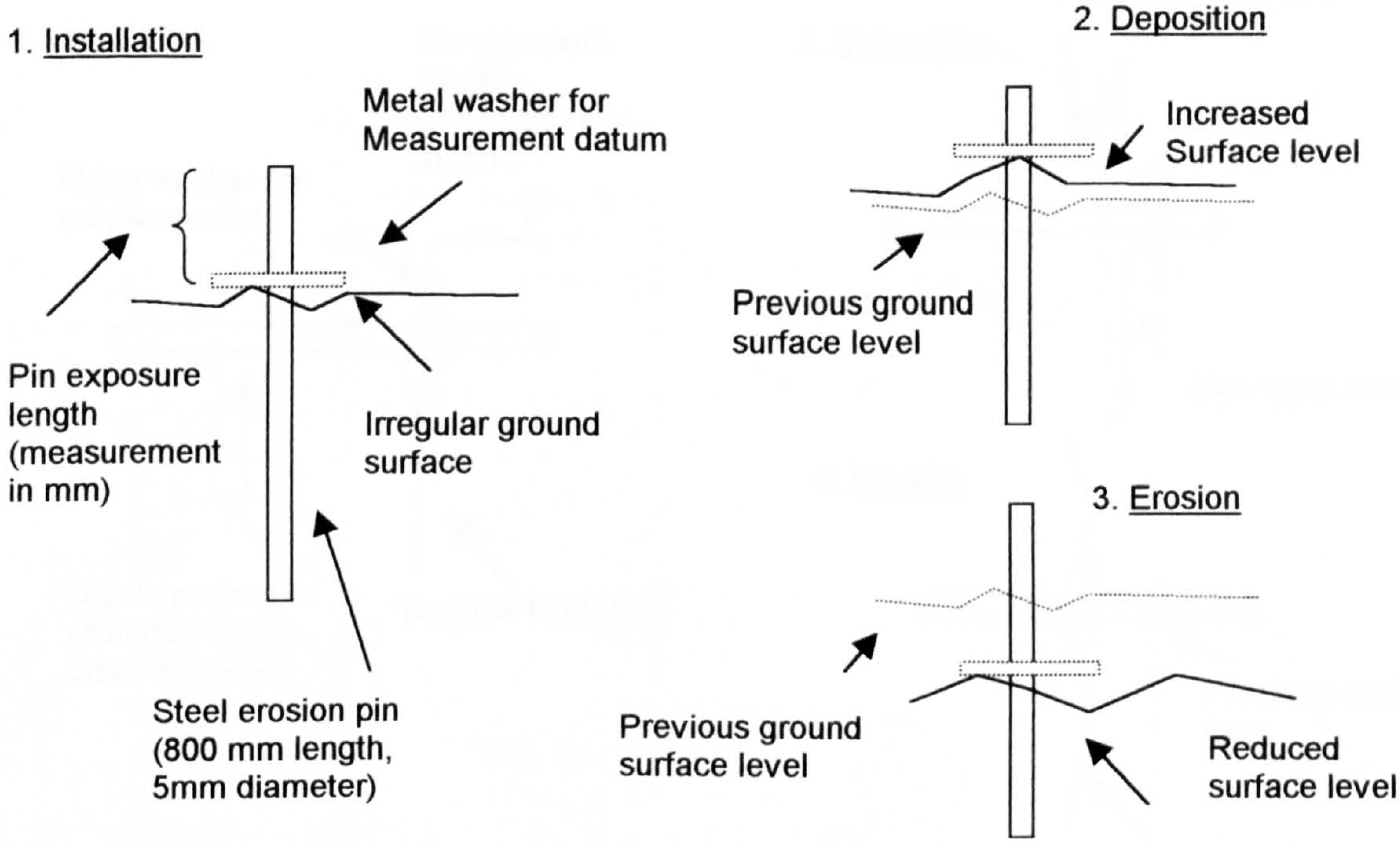


Measurement technique

1. Fix the tape at ground level, from right bank side to left.
2. Measure the vertical and horizontal distance at breaks of slope in the rill cross sectional profile.
3. Repeat for other rill monumented sections.

8. Slope erosion pins

Design Drawing (Not to scale)



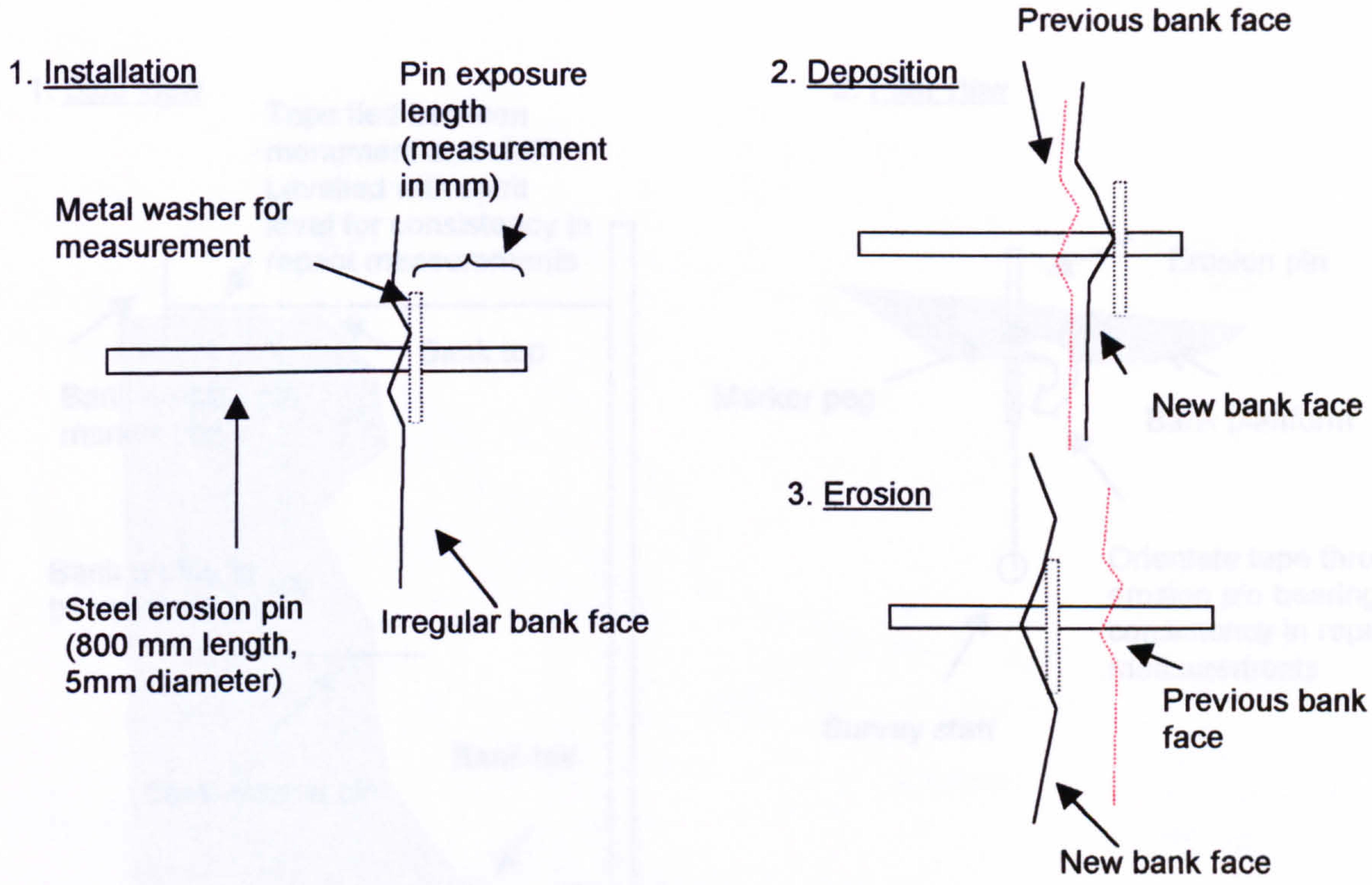
Photograph

Measurement technique

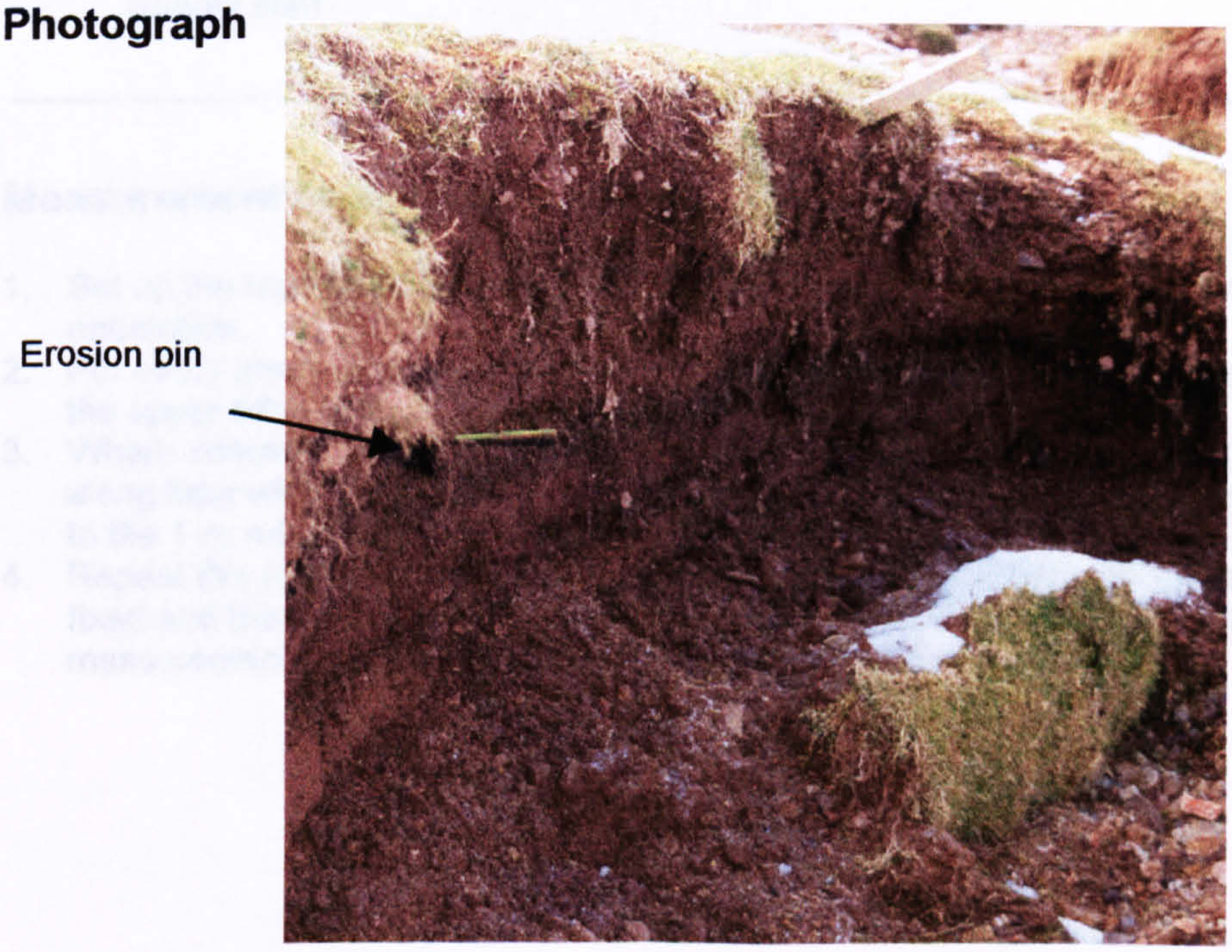
1. Place the washer over the erosion pin (to get a mean surface elevation) and measure the exposure length with an aluminum rule.
2. Repeat for all slope erosion pins.
3. Avoid disturbance upslope of the pins.

9. Channel bank erosion pins

Design Drawing (Not to scale)



Photograph



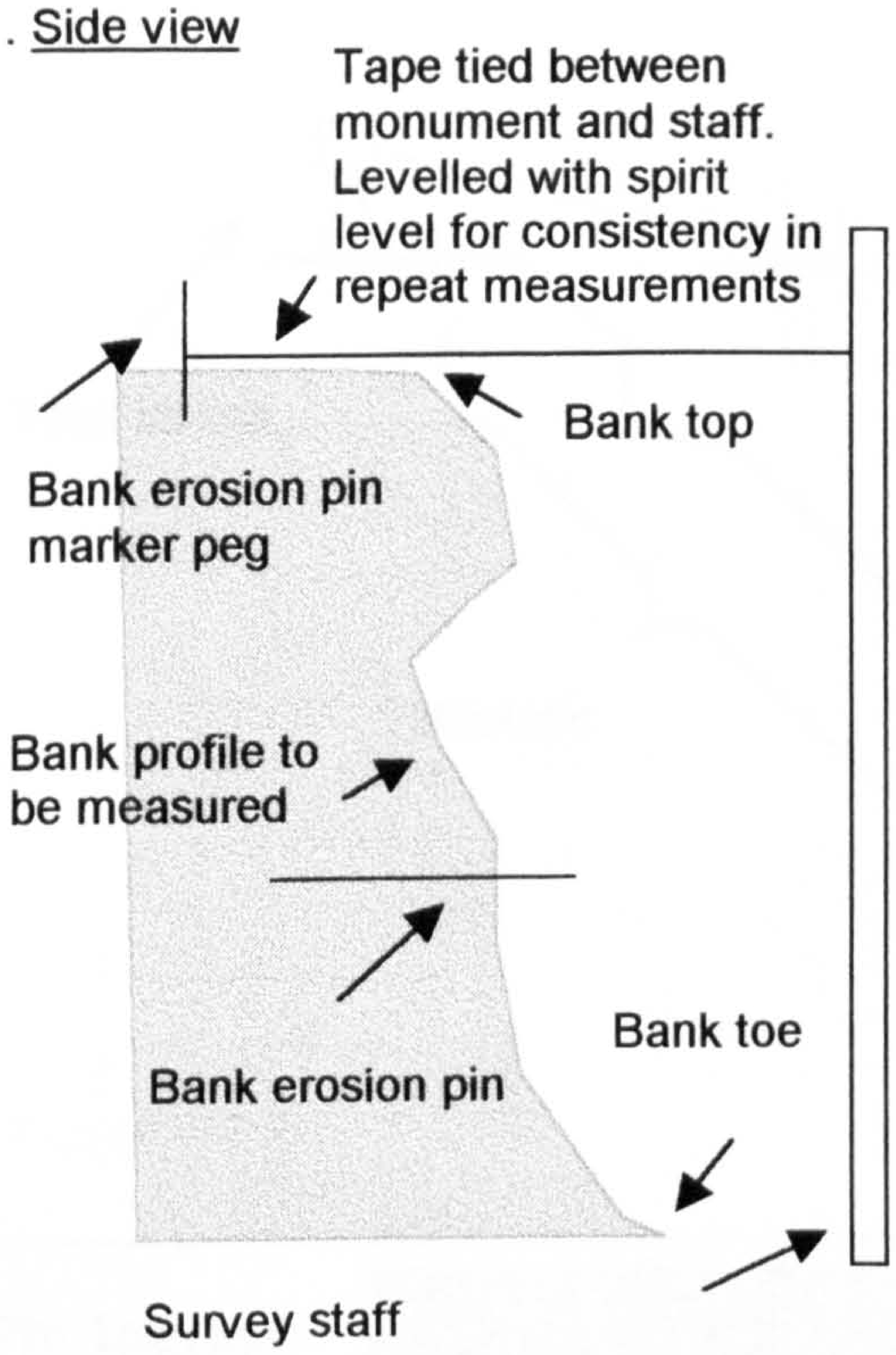
Measurement technique

1. Place the washer over the erosion pin (to get a mean surface elevation) and measure the exposure length with an aluminum rule.
2. Repeat for all bank erosion pins which are visible.

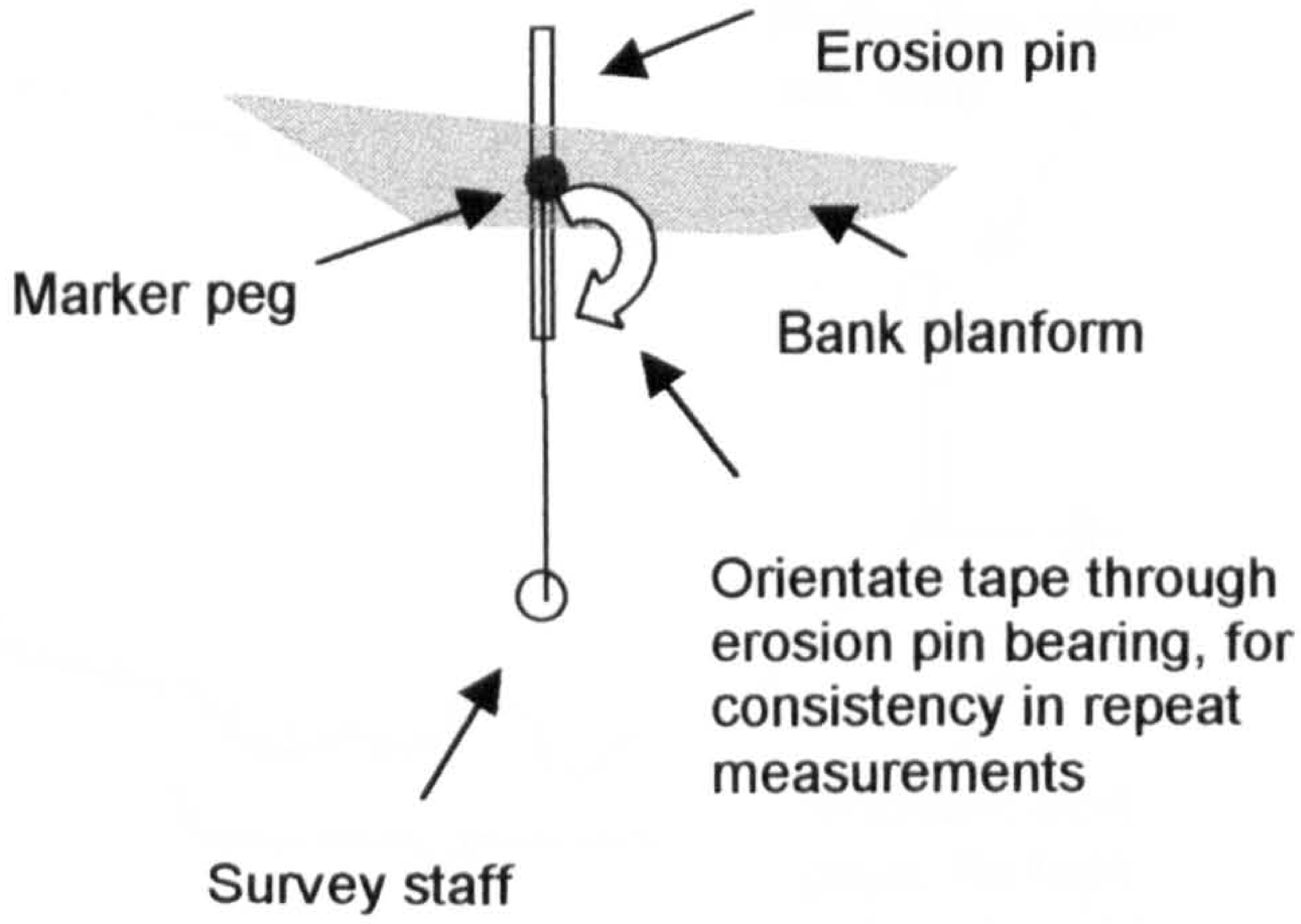
10. Bank profiles

Design Drawing (Not to scale)

1. Side view



2. Plan view

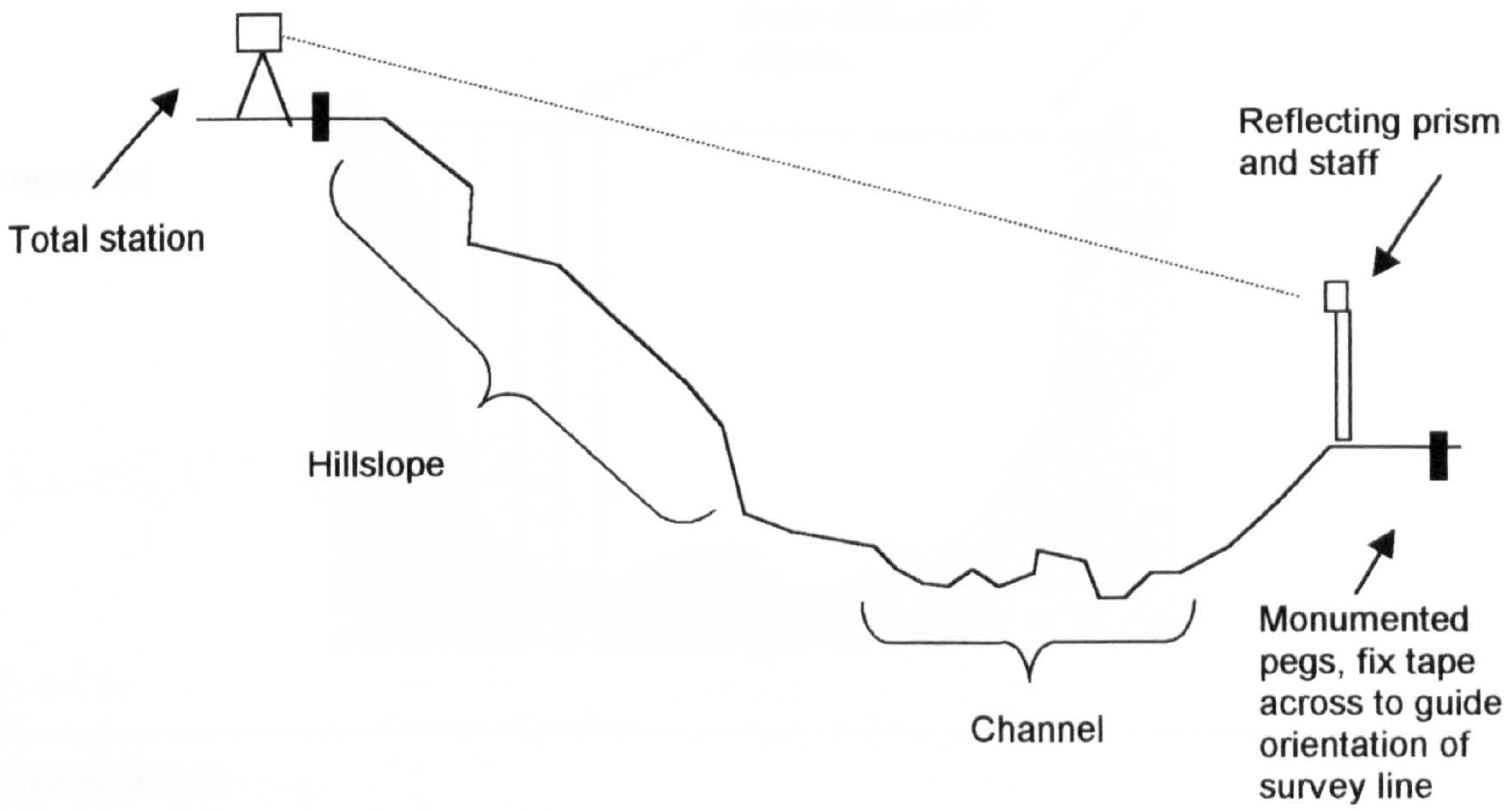


Measurement technique

1. Set up the tape and staff measurement rig. Ensure horizontal level and correct orientation.
2. For every break of slope record the distance along the tape, and measure the depth from the upper edge of the tape with a 1m aluminum rule.
3. Where concavities in the bank profile exist, create a vertical line from a known distance along tape with the a 1m rule, To get the true distance, minus the distance from the bank to the 1 m rule, measured using the 30cm aluminum rule.
4. Repeat this procedure for all bank erosion pin locations, where the marker peg remains fixed and the erosion pin is visible. Both are required to achieve compatibility of measurements between different surveys.

11. Macro cross sections

Design Drawing (Not to scale)



Photograph

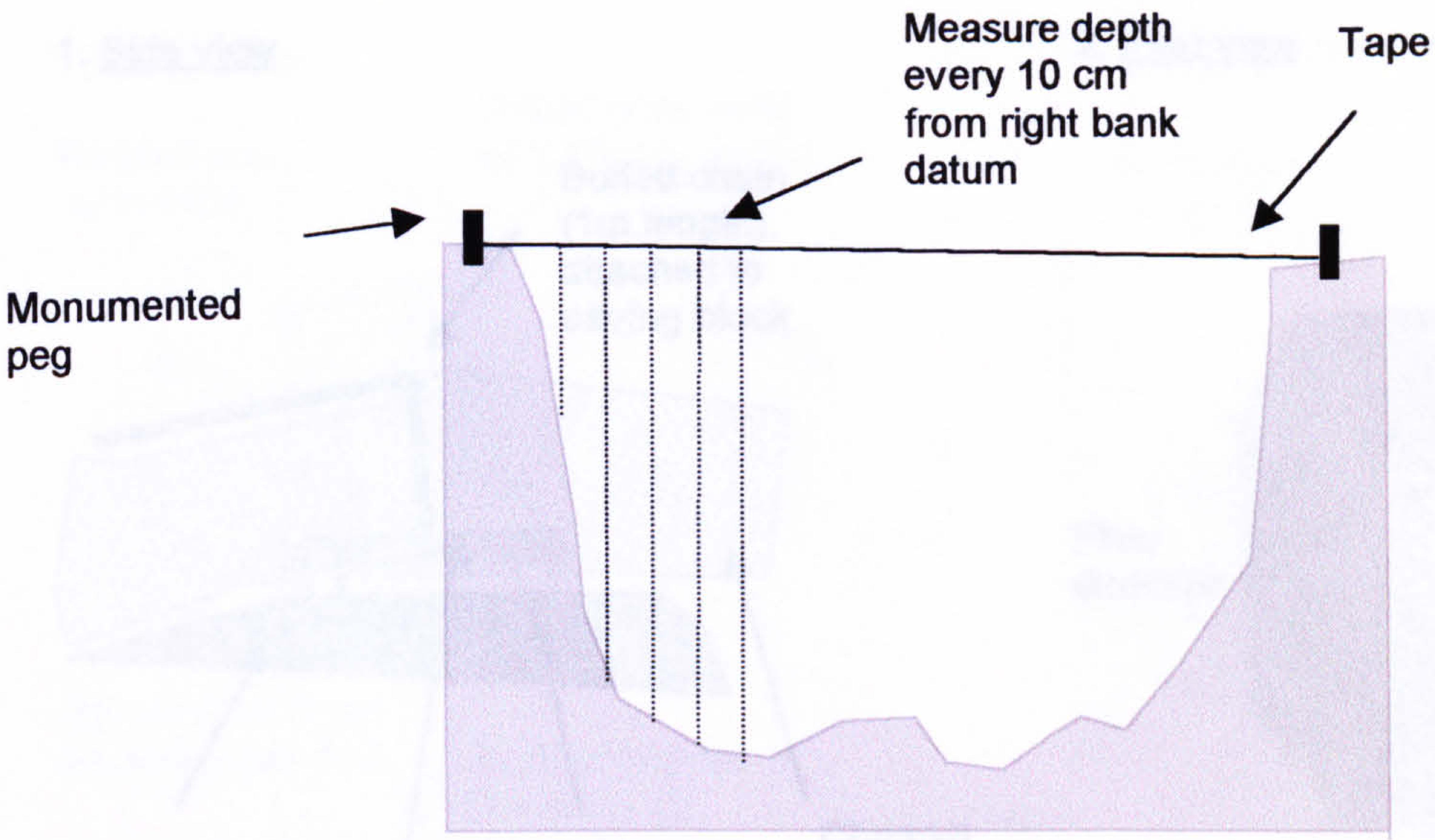
Approximate line of a macro cross section (white line). In this photograph no hillslope component is shown.

Measurement technique

1. Stretch and level tape between the monumented pegs. Setup total station.
2. Measure along the tape line, at changes of slope.
3. Repeat for each macro cross section.

12. Micro cross sections

Design Drawing (Not to scale)



Photograph

White line shows where the tape would cross to form the datum line

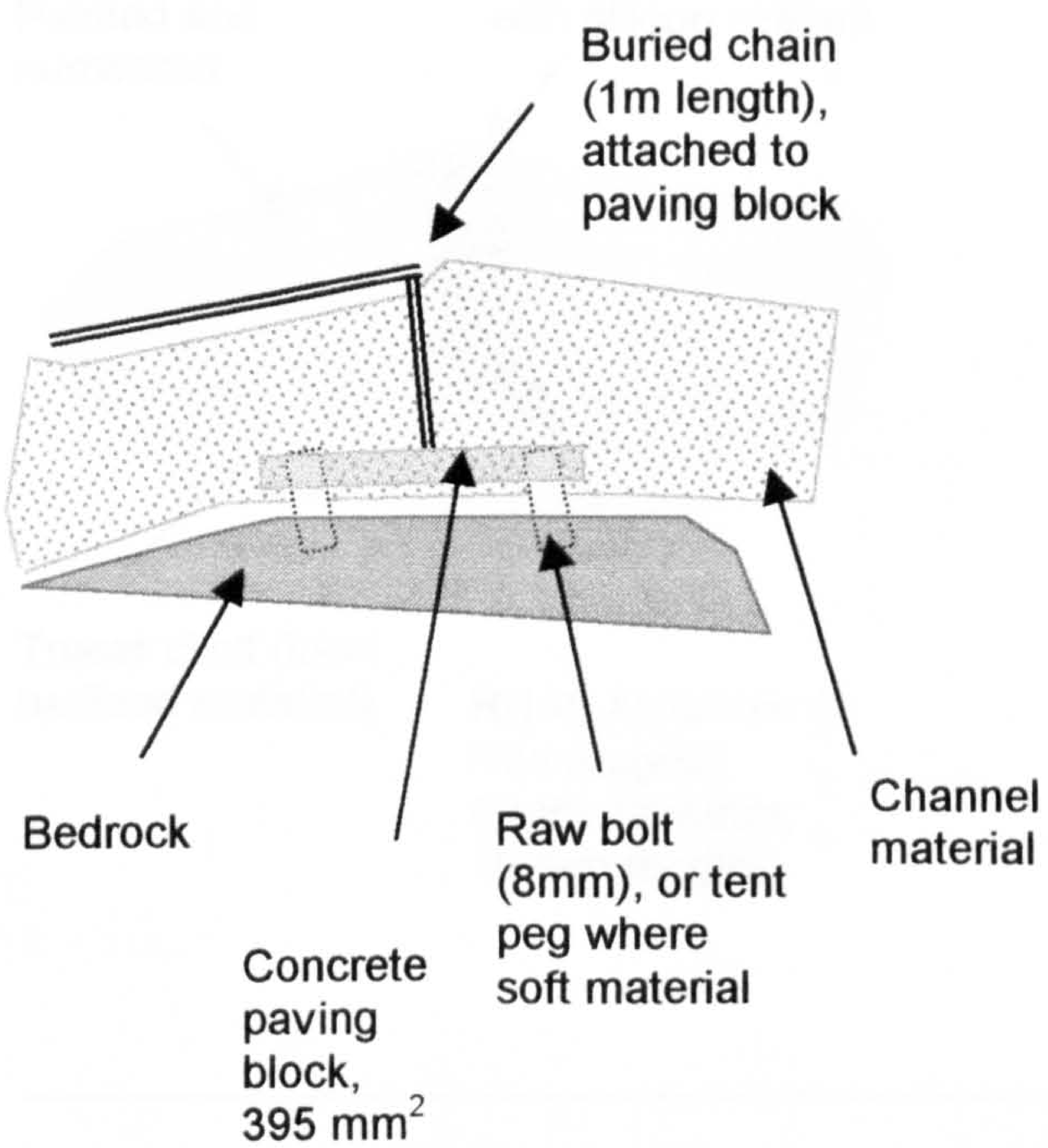
Measurement technique

1. Setup the tape between the pegs (right bank to left), making sure its tight.
2. Note the bank and channel material/features along the length of the tape.
3. Measure depth at 10 cm intervals from the top of the tape, using the 1m aluminum rule.
4. Repeat for all micro cross sections.

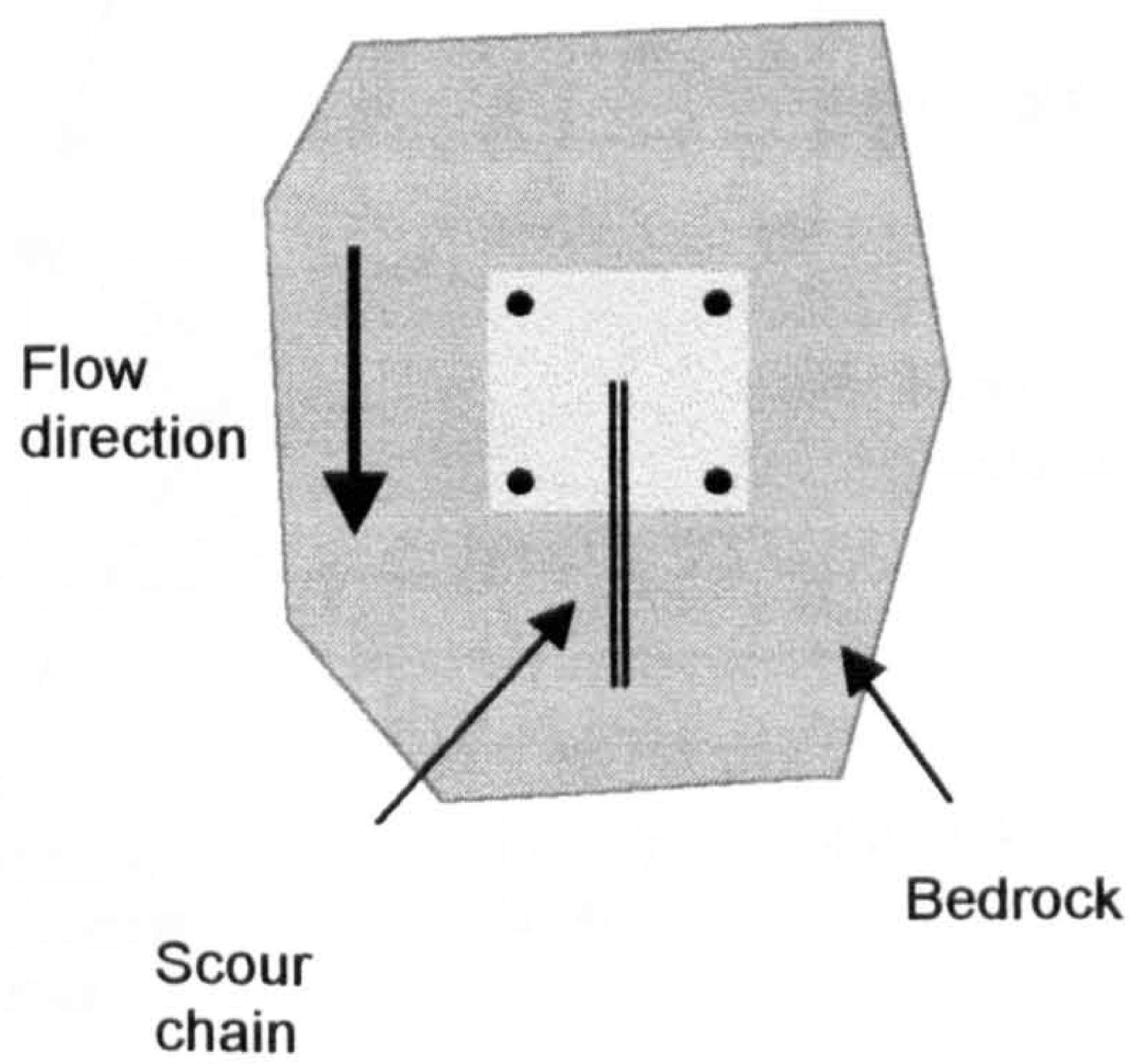
13. Scour chains

Design Drawing (Not to scale)

1. Side view



2. Plan view



Photograph

This is at a location where the bedrock outcrops at the surface. Therefore no burial of the chain is possible. It is therefore rendered largely ineffective.

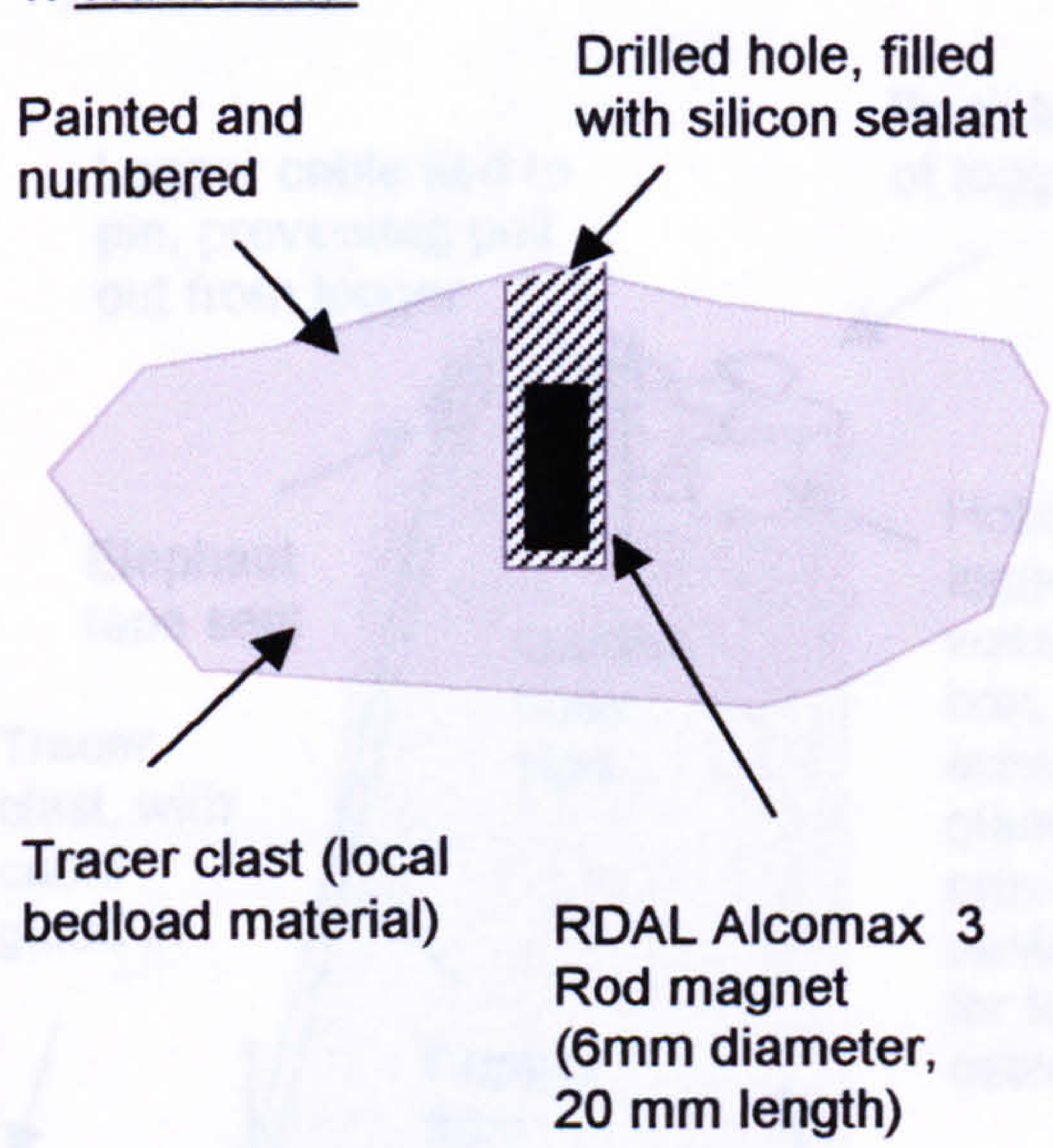
Measurement technique

1. Measure the length of the exposed chain.
2. If erosion occurs the horizontal length of chain will increase, as the vertical length declines and the flow carries the new chain length to the horizontal plane.
3. Deposition is shown by burial of the horizontal chain.
4. The burial depth and process rates effect the measurement life of the scour chain.

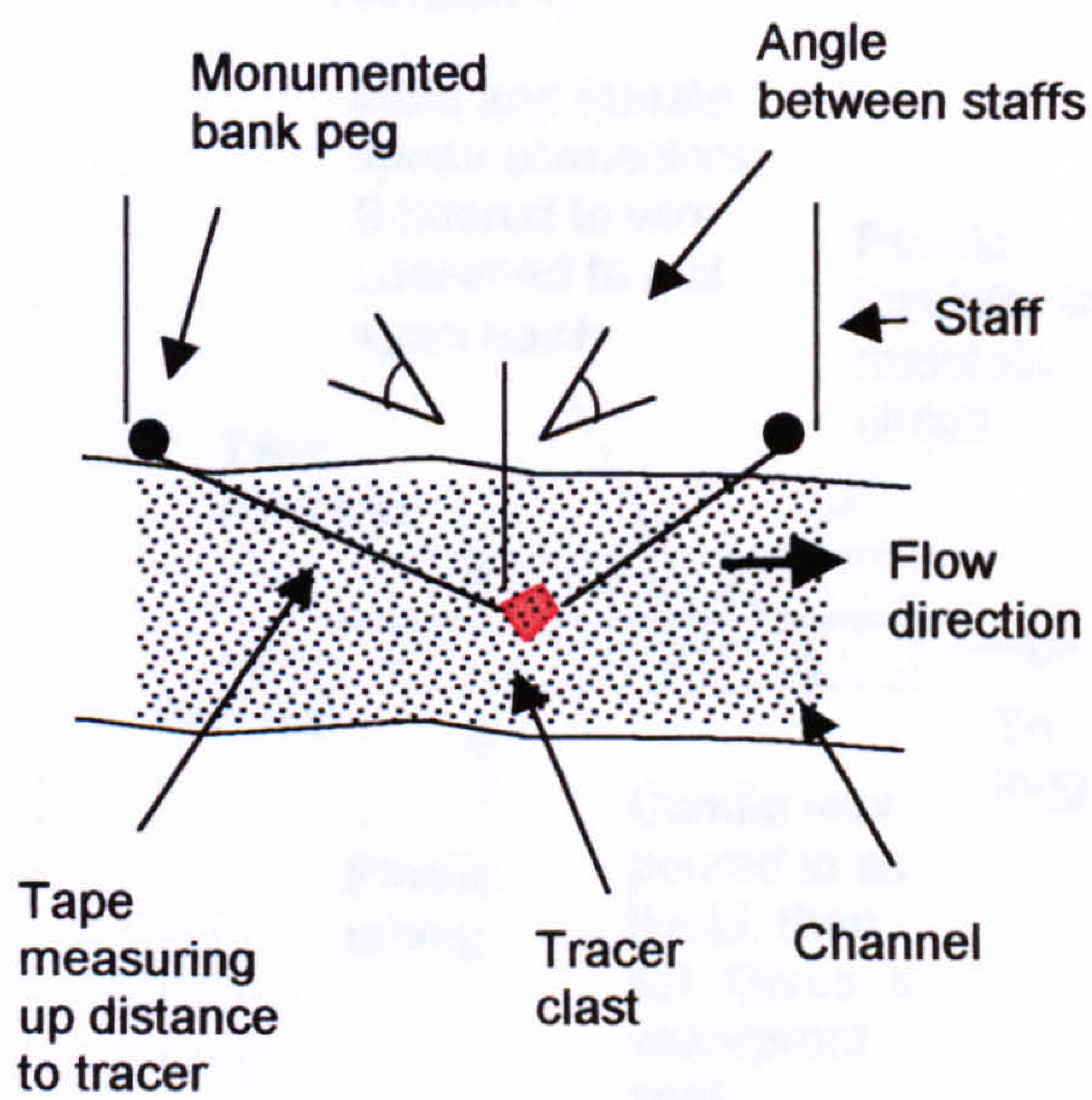
14. Bedload tracer

Design Drawing (Not to scale)

1. Tracer clast



2. Measurement of location (oblique)



Photograph

Left: Tracer series 1, at installation. Cannot bury as Bedrock at Surface

Right: Tracer Clast '136', Buried, found with 'Chicago Steel Tape' Magnet detector

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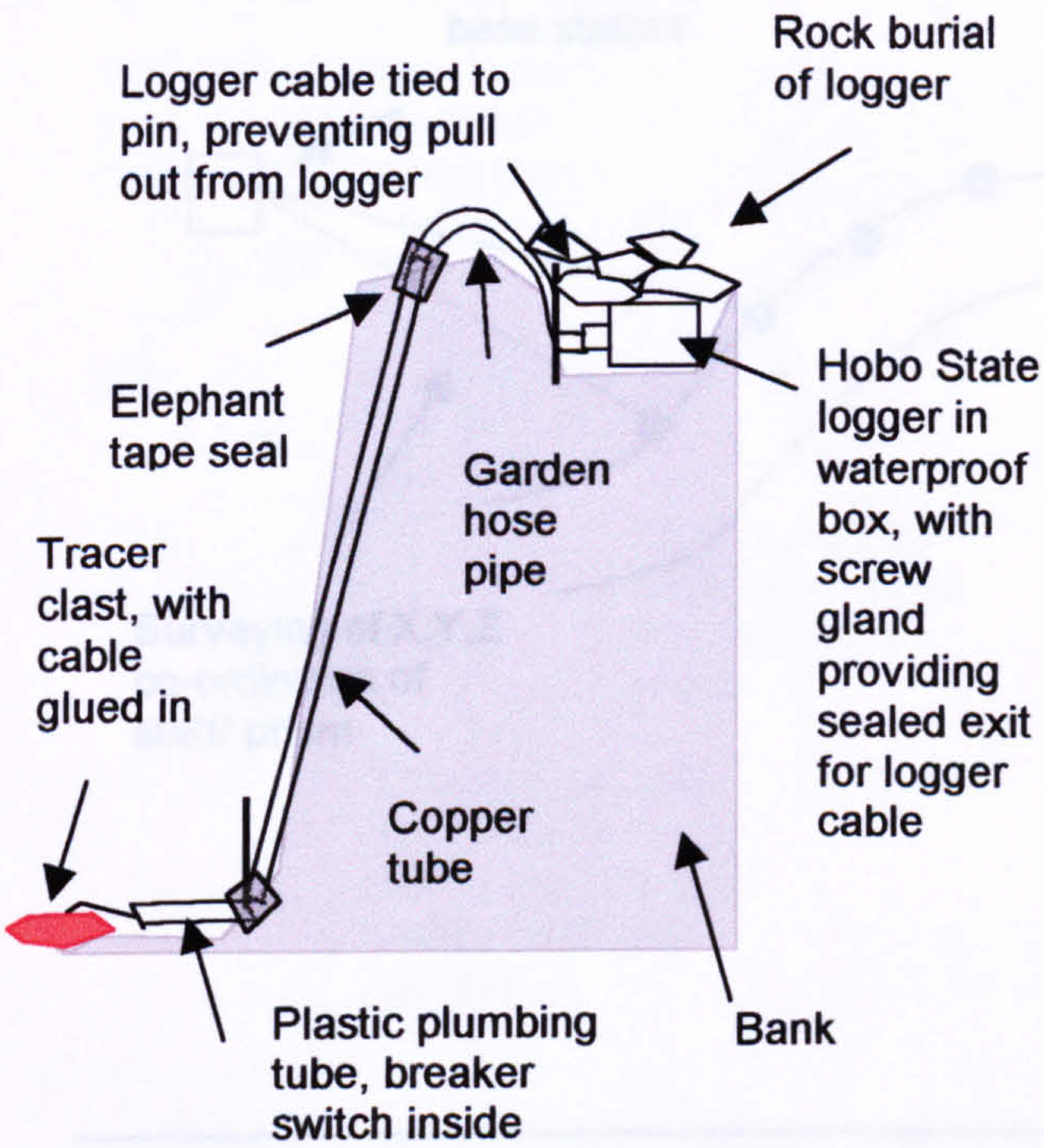
Measurement technique

1. Fix tape measure to first bank monument peg, fix second tape to next peg downstream.
2. Locate tracer visually or with magnetic detecting probe if buried, dig and clear in situ.
3. Identify the tracer number. Then measure up and downslope distances, and measure up and down angles at eye height using staffs.
4. Repeat for all tracer clasts, between all monumented peg pairs where tracers are deposited.

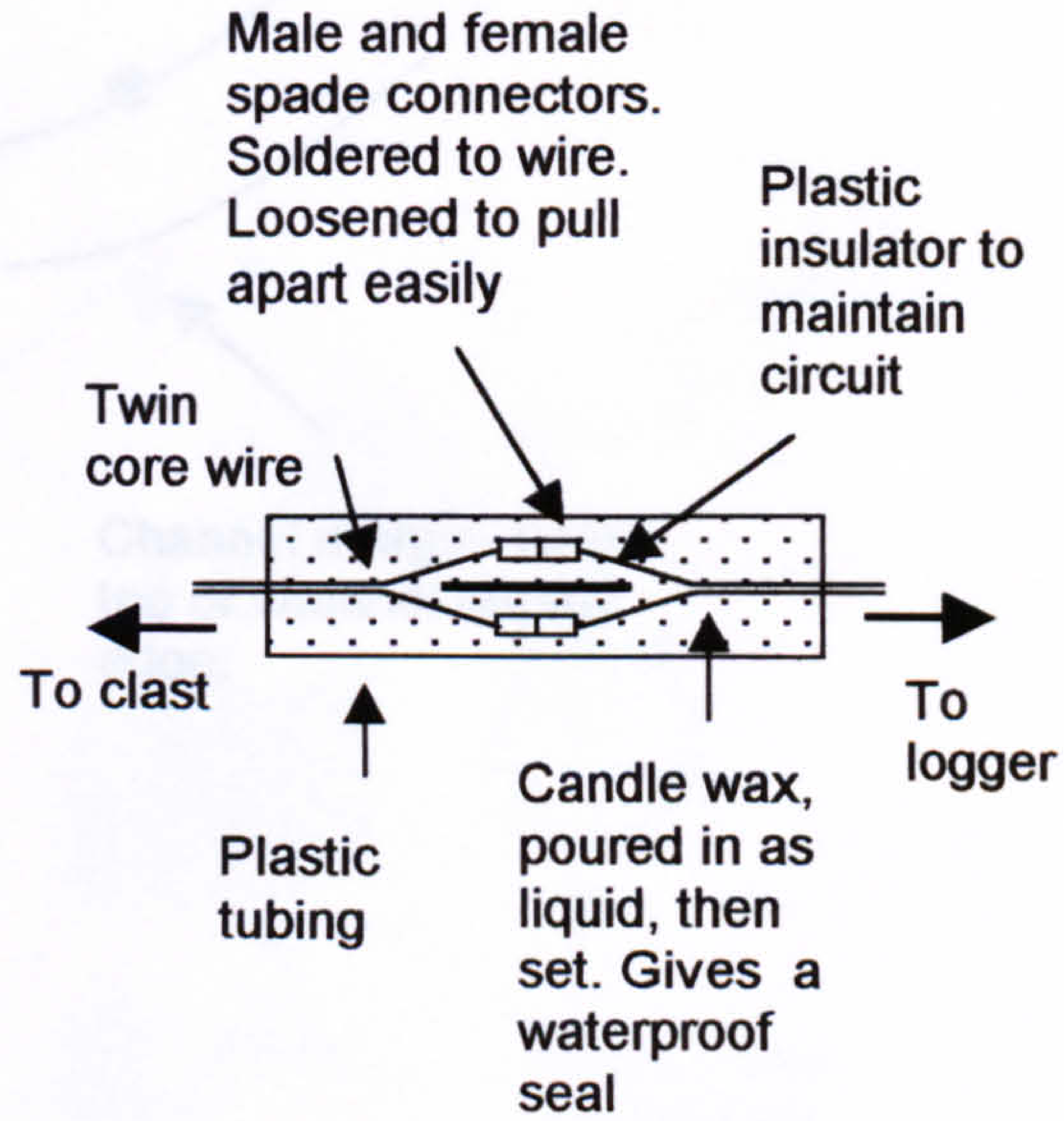
15. Bedload mobilisation timing loggers

Design Drawing (Not to scale)

1.Entire setup



2. Breaker switch design (Version 4)



Photograph

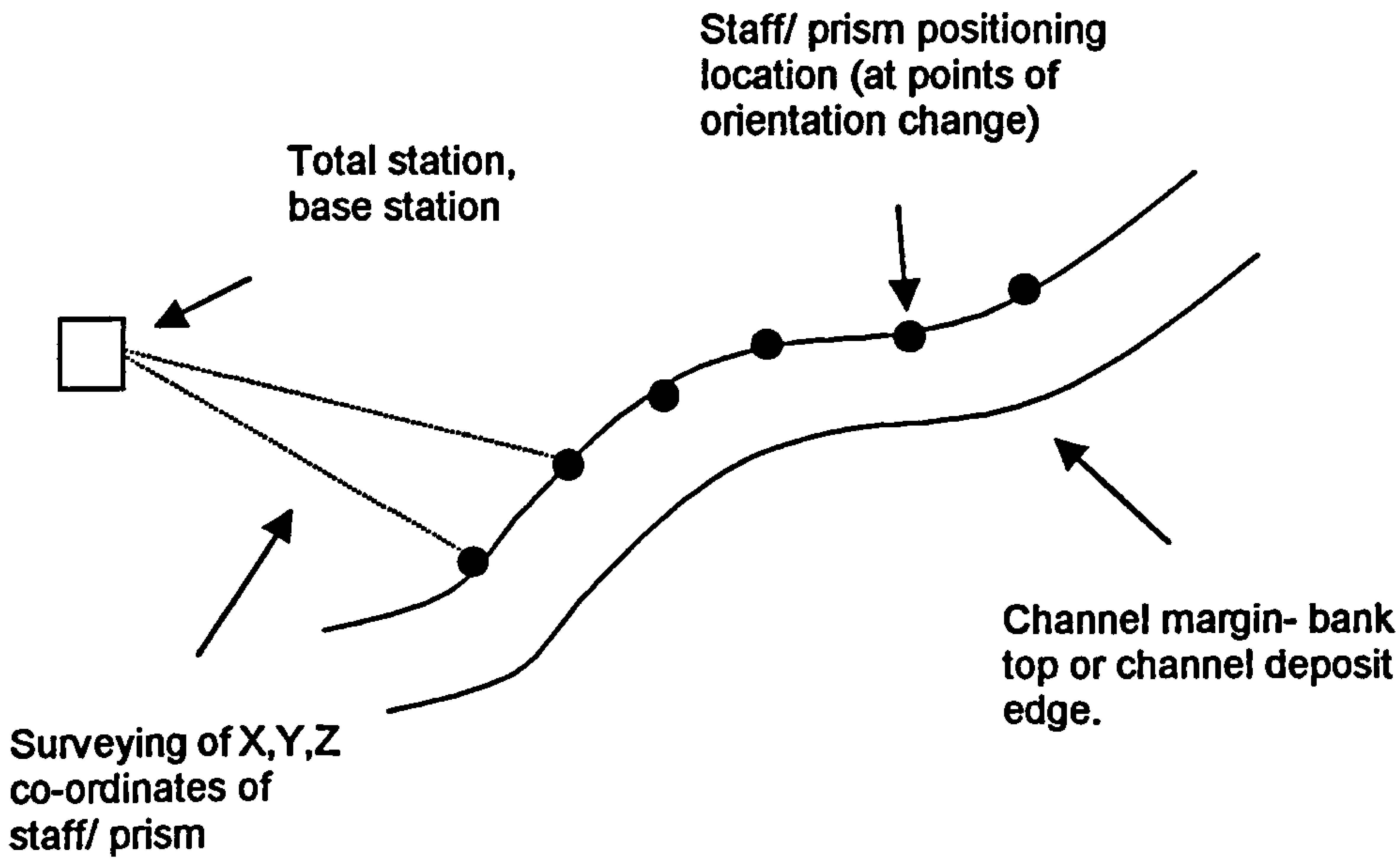
In this case the logger is stored under a box on the hillslope.

Measurement technique

1. Set up equipment as in the design drawing. Launch the logger with the correct time and date.
2. The system remains idle until the circuit is broken by the breaker switch triggering. This separation is caused by the clast pulling at the switch, and eventually breaking free.
3. Downloading the logger reveals the time and date of the change of state in the circuit, thus the time of clast movement.
4. Return the entire monitoring rig to laboratory for rebuild. Reinstall when rebuilt.

16. Channel planform surveys

Design Drawing (Not to scale)



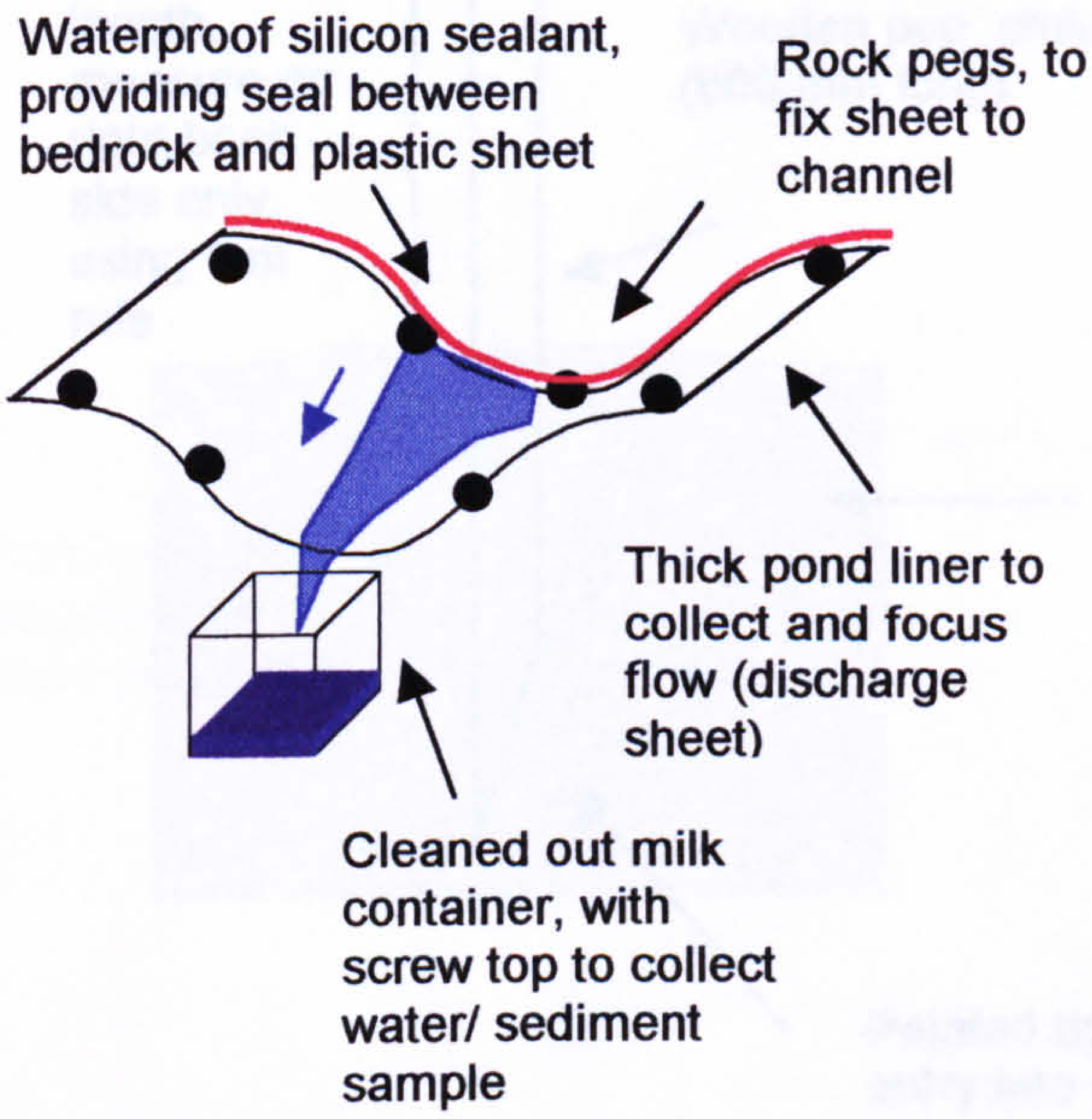
Measurement technique

1. Place total station on monumented TBM, and set orientation of instrument to magnetic north.
2. Survey channel margin of each bank side.

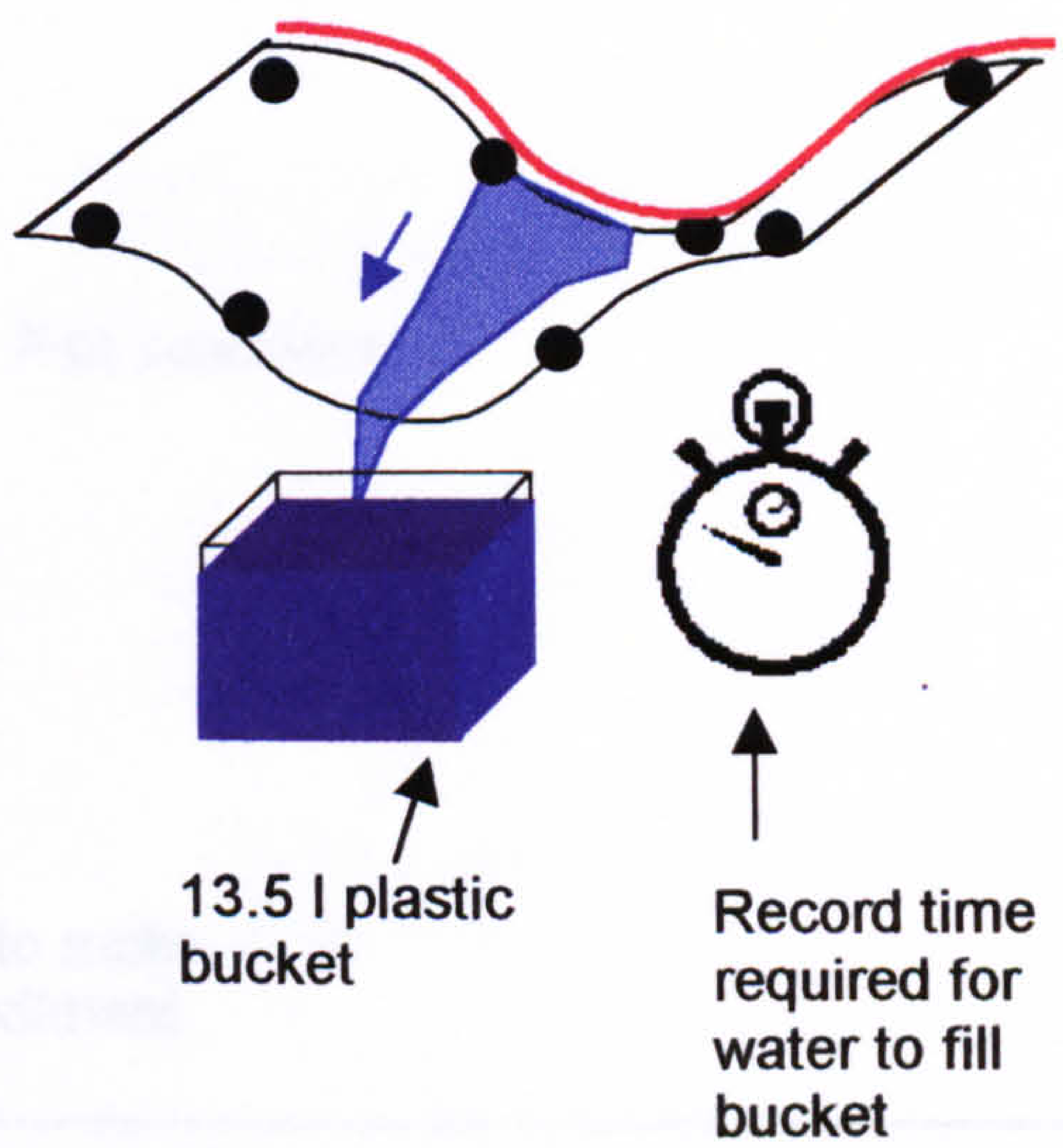
17. Suspended sediment sampling and discharge measurements

Design Drawing (Not to scale)

1. Suspended sediment



2. Discharge measurement



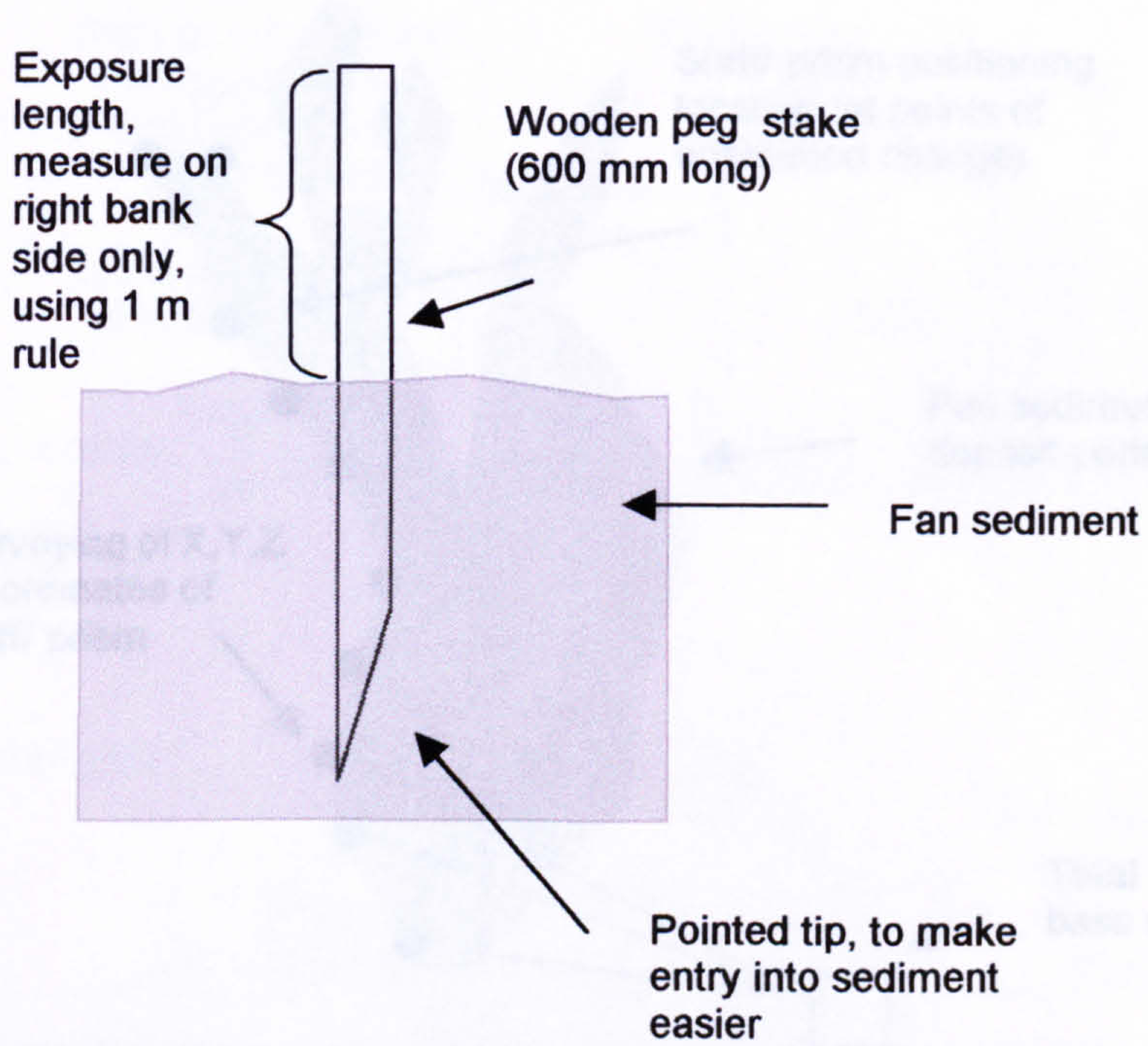
Photograph

Measurement technique

1. Be careful not to walk upstream of the discharge sheet. Wash out the milk bottle with the local water. Collect water sample then seal and label with time, date, and location.
2. Perform the discharge measurement, by filling bucket to the brim and record the filling time. Repeat three times to give an average measure of flow rate.
3. Repeat the suspended sediment and discharge sampling at all the discharge sheets if they are operational.

18. Fan peg array

Design Drawing (Not to scale)



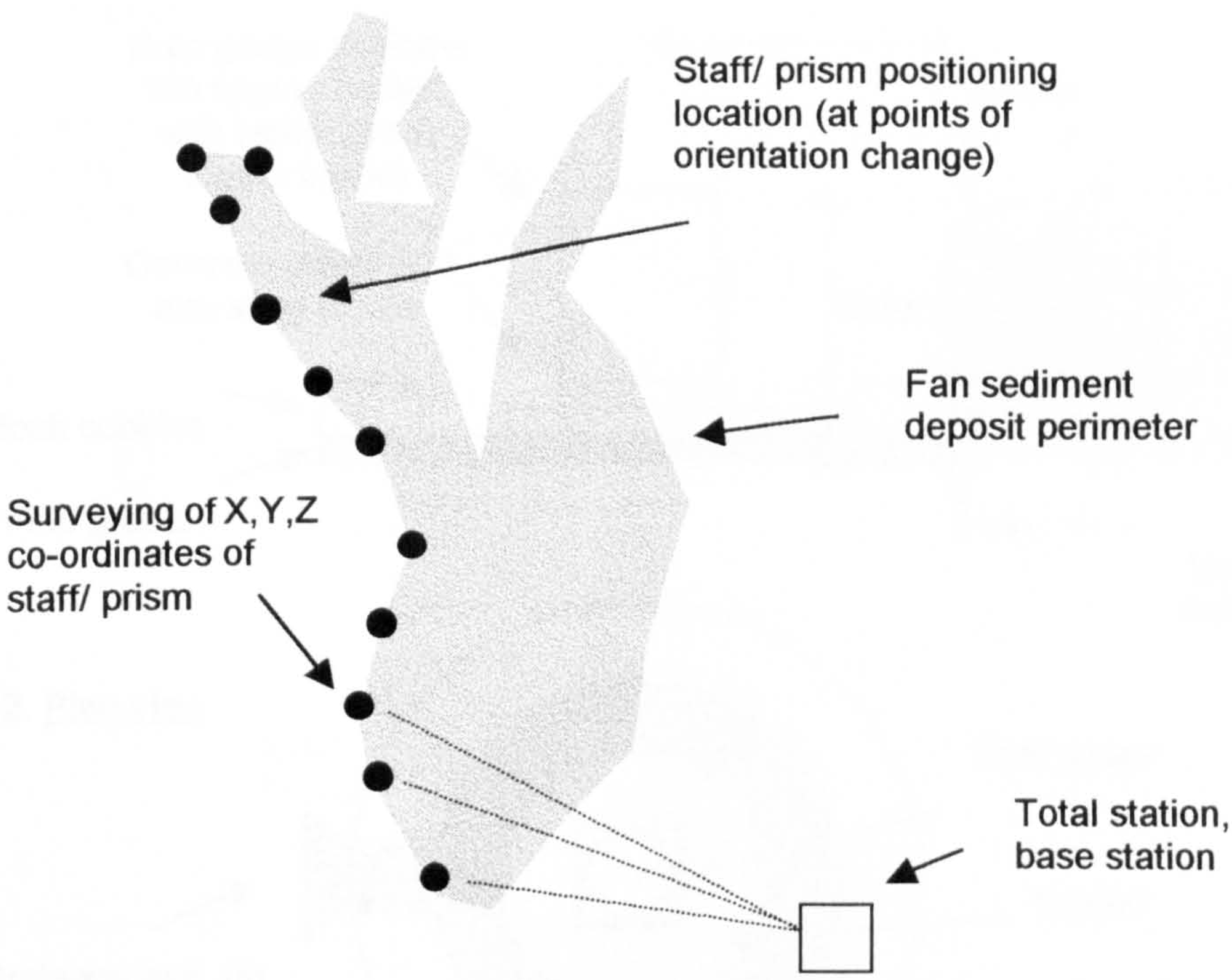
Photograph

Measurement technique

1. Measure the exposure length of the stake, on right bank side. Also note whether the ground surface is grass, or sediment.
2. Repeat measurement for all peg array stakes across the fan surface.

19. Fan deposit surveys

Design Drawing (Not to scale)

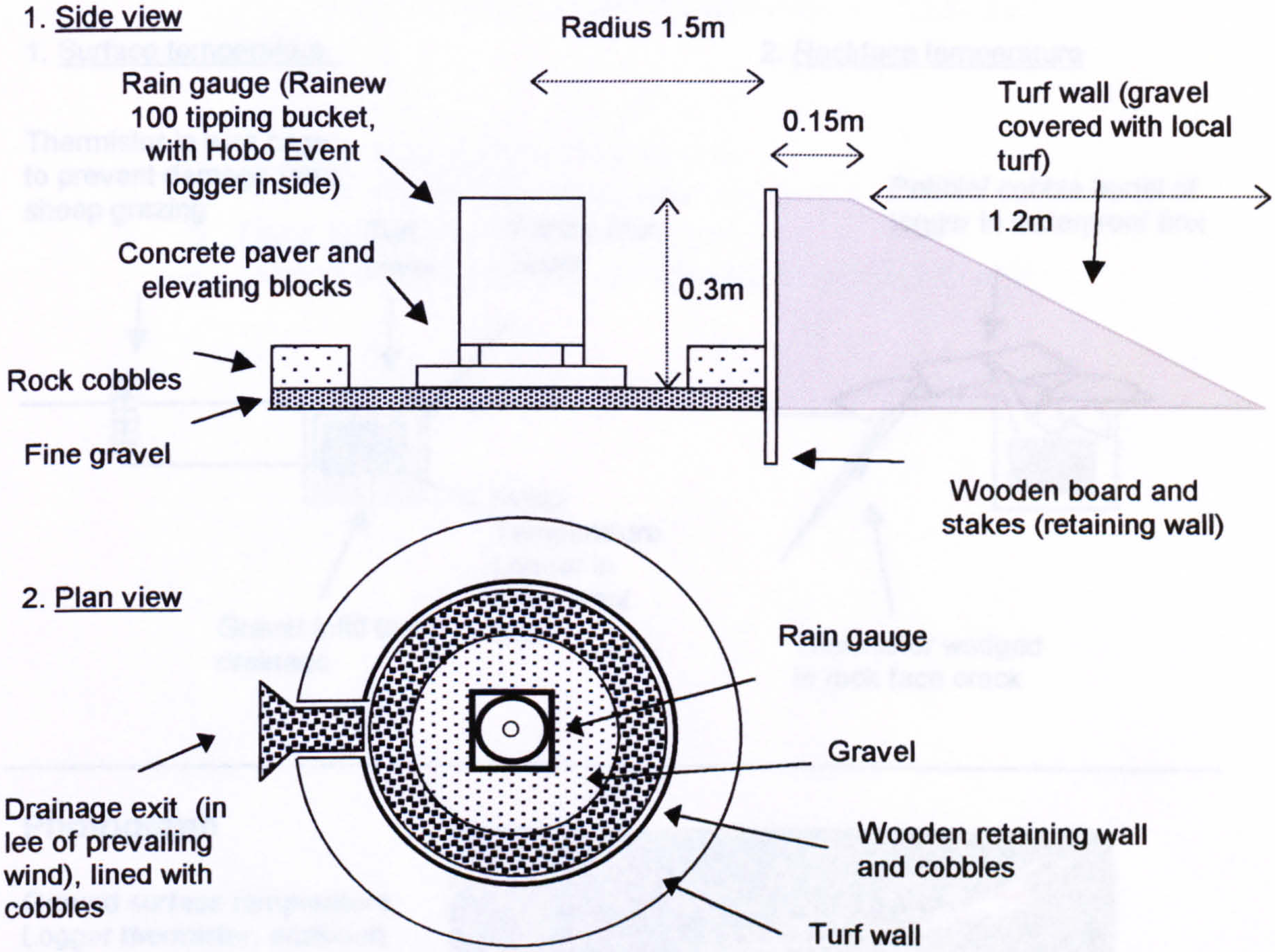


Measurement technique

1. Place total station on monumented TBM, and set orientation of instrument to magnetic north.
2. Survey fan perimeter segments

20. Rain gauge

Design Drawing (Not to scale)



Photograph

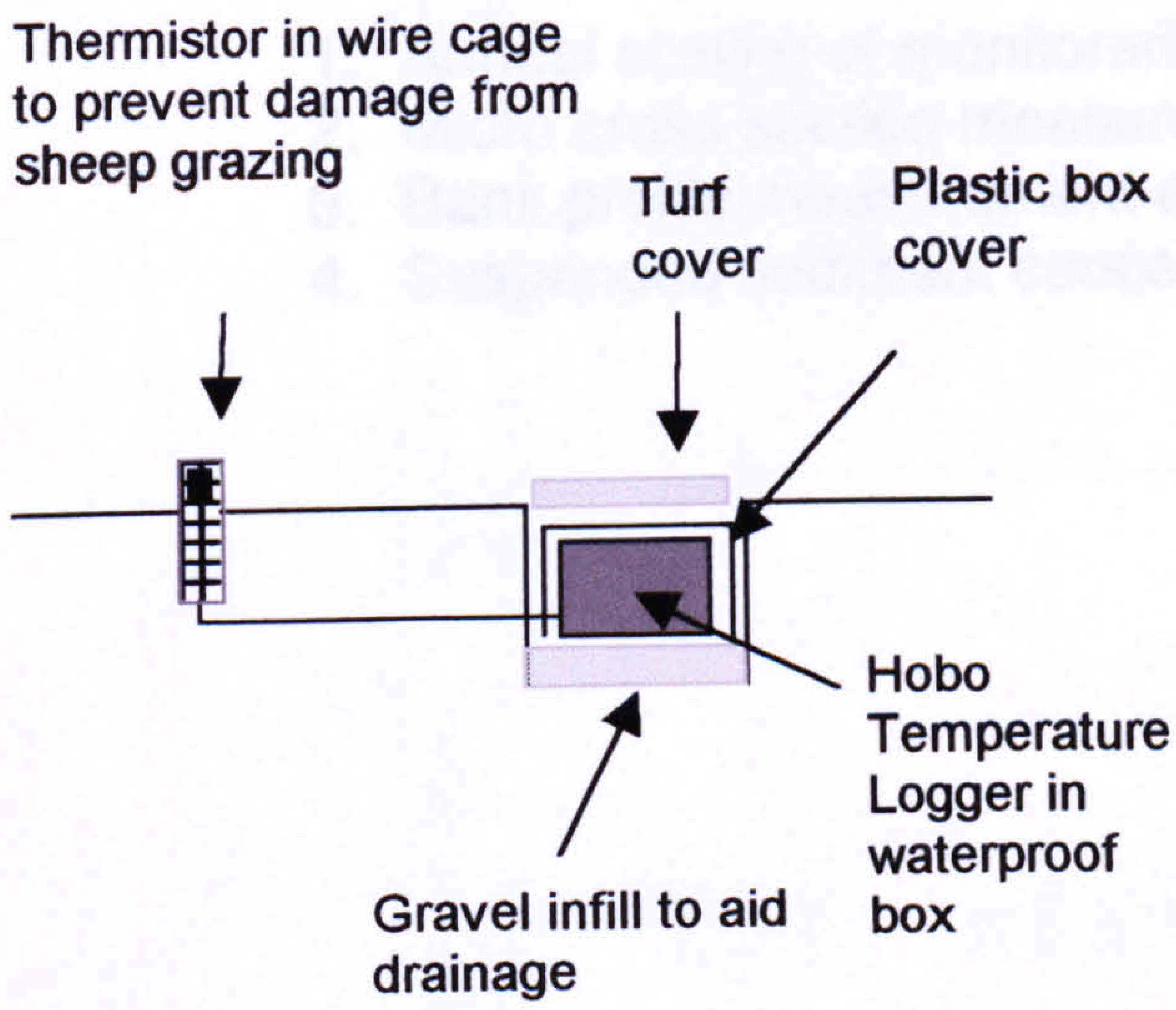
Measurement technique

1. Open up the rain gauge, attach the laptop via the download cable to the logger. Download the data. Then relaunch the logger with the correct time and data. Record logger info.
2. Check the operation of the tipping bucket and clean out the collection funnel.

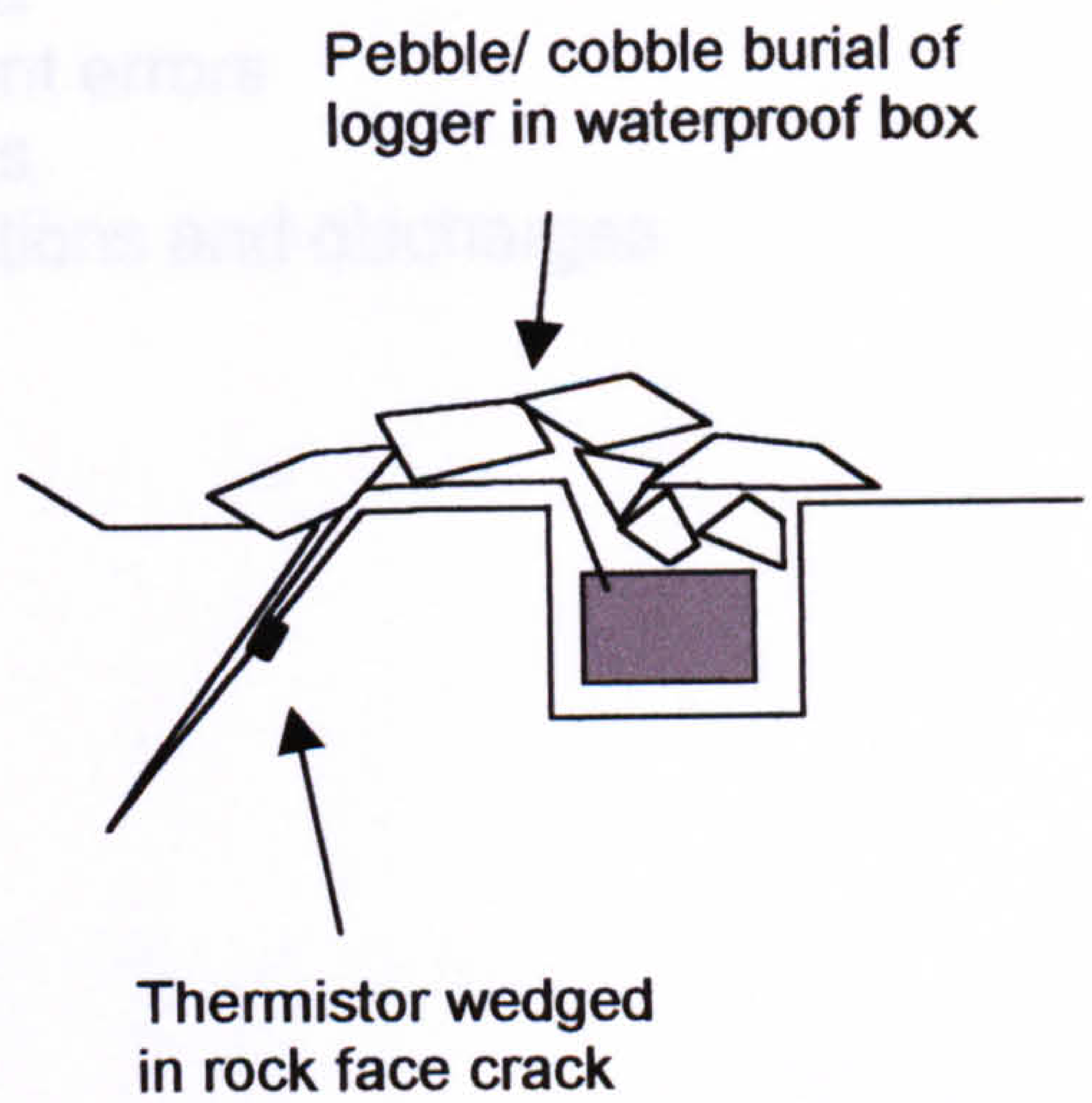
21. Temperature logging

Design Drawing (Not to scale)

1. Surface temperature



2. Rockface temperature



Photograph

Ground surface temperature Logger thermistor, enclosed by cage.

Measurement technique

1. Locate the logger, and remove from the ground. Unscrew the cover of the waterproof box. Attach laptop to the logger via the downloading cable.
2. Download temperature data.
3. Relaunch logger with correct time and date, and record the information displayed about the logger download and relaunch. Reseal waterproof box and bury logger.
4. Check the location and state of the thermistor.

APPENDIX 5.2

SUPPLEMENTARY MATERIAL FOR THE IRON CRAG TORRENT SEDIMENT BUDGET

1. Annual scaling of monitored data
2. Micro cross section measurement errors
3. Bank profile measurement errors
4. Suspended sediment concentrations and discharges

Appendix 5.2- 1: Annual scaling of monitored data

Instrument type	Monitoring Start (Selected date)	Monitoring end	Number of days	Shortfall In days	Scaling Factor to achieve 365
Gerlach trough					
(Primary)	18.1.99	4.12.99	330	35	1.0959
(Sub-Primary)	29.12.98	4.12.99	340	25	1.0685
(Secondary)	12.12.98	4.12.99	357	8	1.0219
Net					
(Primary)	7.1.99	4.12.99	331	34	1.0932
(Sub-Primary)	13.12.98	4.12.99	356	9	1.0247
(Secondary)	13.12.98	4.12.99	356	9	1.0247
(Bedrock step)	13.12.98	4.12.99	356	9	1.0247
Bank profile	18.12.98	7.12.99	354	11	1.0301
Micro cross section	17.12.98	7.12.99	355	10	1.0274
Fan peg array	12.12.98	6.12.99	359	6	1.0164

Appendix 5.2- 2: Micro cross-section measurement errors

Cross section	Measurement Interval end	Measured change (cm^2)	Mean test error (cm^2)	Error contribution (%)
2	2	778	64	8
	7	812	64	8
	9	389	64	16
	10	367	64	17
	11	650	64	10
	12	171	64	37
	13	260	64	24
	14	126	64	51
	15	343	64	19
	17	589	64	11
	18	402	64	16
	19	508	64	13
	20	888	64	7
	21	1776	64	4
	22	47	64	135
3	2	80	39	49
	7	642	39	6
	9	104	39	37
	10	199	39	20
	11	57	39	68
	12	69	39	56
	13	458	39	8
	14	245	39	16
	15	75	39	52
	17	154	39	25
	18	91	39	43
	19	528	39	7
	20	506	39	8
	21	822	39	5
	22	892	39	4
5	2	4	4	113
	7	1501	4	0
	9	726	4	1
	10	695	4	1
	11	150	4	3
	12	12	4	35
	13	7	4	60
	14	97	4	4
	15	916	4	0
	17	467	4	1
	18	251	4	2
	19	256	4	2
	20	1015	4	0
	21	555	4	1
	22	658	4	1
10	2	100	43	43
	7	1281	43	3
	9	1635	43	3
	10	284	43	15
	13	2344	43	2
	14	53	43	81
	15	1044	43	4
	17	937	43	5
	18	271	43	16
	19	228	43	19
	20	912	43	5
	21	1135	43	4
	22	318	43	13
			Mean	20.933
			Median	**9.142**
			St. Dev	27.708

Appendix 5.2- 3: Bank profile measurement errors

Bank Profile	Measurement Interval end	Measured change (cm^2)	Mean test error (cm^2)	Error contribution (%)
2	7	520	101	19
	12	206	101	49
	13	115	101	88
	18	203	101	50
	21	388	101	26
	22	165	101	61
8	7	99	68	68
11	7	250	10	4
	12	199	10	5
	13	854	10	1
	18	237	10	4
	21	58	10	17
	22	5133	10	0
16	7	20	44	227
	12	52	44	86
	18	26	44	169
	21	98	44	46
17	7	420	55	13
	13	309	55	18
	18	286	55	19
	21	358	55	15
	22	248	55	22
18	7	1008	21	2
	12	141	21	15
	13	256	21	8
	18	222	21	9
32	7	315	27	8
	12	171	27	16
	13	203	27	13
	18	48	27	55
	21	154	27	17
	22	90	27	30
34	7	76	36	47
	12	224	36	16
	13	143	36	25
	18	271	36	13
	21	27	36	134
	22	64	36	56
			Mean	38.721
			Median	18.602
			St Dev.	48.150

Appendix 5.2- 4: Calculation of representative discharge and suspended sediment values for both storm and baseflow conditions. Using data from the rain event of the 26.11.99, and the collection of individual samples obtained throughout the sediment budget monitoring period. All the data is sorted in each column, so data in rows are not corresponding measurements (*- data from storm conditions 6.12.99- largest discharge event witnessed).

Data	Baseflow: 26.11.99		Baseflow: collected data		Storm: 26.11.99		Storm: collected data
	Discharge ($l\ s^{-1}$)	Suspended sediment ($mg\ l^{-1}$)	Discharge ($l\ s^{-1}$)	Suspended sediment ($mg\ l^{-1}$)	Discharge ($l\ s^{-1}$)	Suspended sediment ($mg\ l^{-1}$)	Discharge ($l\ s^{-1}$)
Data ($l\ s^{-1}$)	0.40	0.24	0.01	0.32	0.79	4.94	7.25 (*)
	0.41	0.92	0.03	0.45	0.93	14.93	
	0.41	1.11	0.04	0.52	1.04	21.51	
	0.41	1.46	0.05	0.91	1.09	27.56	
	0.41	1.46	0.05	1.16	1.14	40.22	
	0.41	1.62	0.08	1.32	1.21	50.61	
	0.41	1.75	0.14	1.79	1.21	51.74	
	0.42	1.88	0.15	2.17	1.36	186.99	
	0.42	2.62	0.16	3.23	1.40	329.38	
	0.43	2.73	0.20	3.35			
	0.43	2.98	0.29	4.67			
	0.43	3.33	0.29	4.78			
	0.43	3.46	0.31	5.43			
	0.43	5.87	0.32	5.45			
	0.43	6.32	0.34	6.55			
	0.43	8.35	0.37	7.34			
	0.43	8.92	0.38	10.52			
	0.44	11.49	0.45	16.48			
	0.45	11.83	0.59	22.74			
	0.45	14.41	0.60	37.05			
	0.45	17.39	0.88	50.11			
	0.45	22.56	0.98	66.12			
	0.46	25.14					
	0.46	31.08					
	0.46	38.79					
	0.47	41.60					
	0.64	52.62					
Maximum	0.64	52.62	0.98	66.12	1.40	329.38	**7.25**
Minimum	0.40	0.24	0.01	0.32	0.79	4.94	-
Mean	**0.44**	**12.19**	**0.31**	**11.48**	**1.13**	**80.87**	-
Standard Dev.	0.04	14.14	0.27	17.58	0.20	107.77	-
n	28	28	22	22	9	9	1

APPENDIX 8.1

PRO FORMA CHECK SHEETS USED DURING THE FIELD MEASUREMENT PHASE OF THE REGIONAL SURVEY OF THE HELVELLYN AND SKIDDAW MASSIFS

1. General cover sheet used at all sites
2. Sheets specific to torrents (2-5)
3. Sheets specific to hillslope debris flows (1-3)
4. Stratigraphic log

TORRENT/ HILLSLOPE DEBRIS FLOW LDNP
Cover sheet

Site Info:

Sheet completed by-

Massif-

Site name (location specific)

Grid reference-

Top altitude-

Bottom altitude-

Aspect (magnetic)-

Feature type-

Label number-

RISK FEATURES:
(Yes/No; Number; Distance away; Past/ current damage)

Buildings

Path

Road

Bridge

Railway

Powerline

Pipe network

Engineering control structure

Stream/ river at site

Stream/ river upstream

Stream/ river downstream

Agricultural land

INTERFERENCE FEATURES

Engineering modification on or around site-

Sheep grazing-

Other animals-

CONTEXTUAL SITE FEATURES

General description & evolution-

Vegetation (type, amount)-

Drainage (surface, pattern, number)-

Slope angle-

Aspect-

Evidence of instability-

Evidence of past activity-

Surface sediment-

DRAINAGE

Springs-

Active surface flow- start and end positions-

Connectivity to surrounding landscape-

Topographic concavities-

Standing water-

Man made drainage/ diversions

VEGETATION

Is the site vegetated-

To what extent is it vegetated

Damage-

Creep indication-

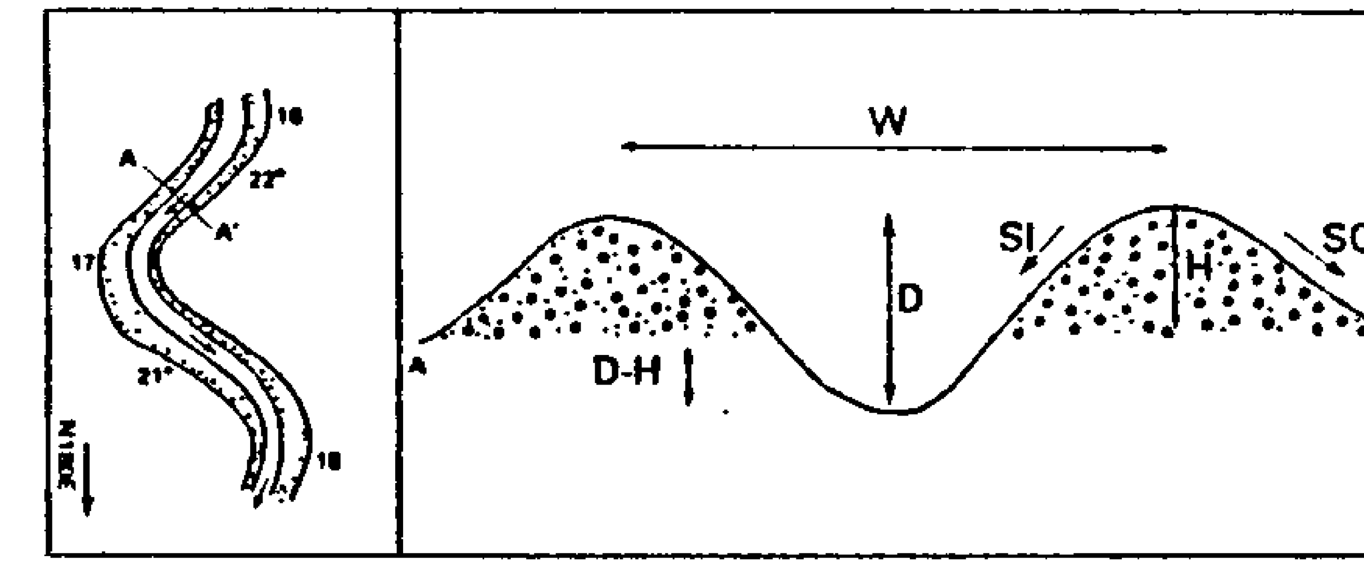
Main Channel FLUVIAL (Test to see if valid for Paleohydrological techniques. Test high probability sites only) TORRENTS (Sheet 2)

LOCATION			
G.R + label on g. map-			
Alt.-			
Aspect-			
REACH TEST			
Erosional or depositional reach?			
Is section uniform, straight			
Signif. Length (20W, 75 mean h20 D)			
Bedrock			
BOULDER TEST			
Independent or collective?			
Multiple large rocks & XS rocks?			
In situ or deposited boulders			
Fluvial deposit?			
Pan handle/ non uniform reach			
Lichens?			
REACH MAP (1. Diff deps, 2. Spatial distrib. 3.large boulders. 4. Gen. geomorph)			
REACH DETAILS			
Channel slope-			
Palaeo stage slope-			
Cross section bankfull (multiple)-			
Cross section past stage -			
Mannings 'n'-			
PSA section-			
Material storage volume in xs-			
BOULDER DETAILS			
Imbrication angle-			
Particle sample (for lith, density)-			
Boulder ABC of distribution-			
Lichenometry of all B. &/ or B. dep. Group.-			
Photography-			

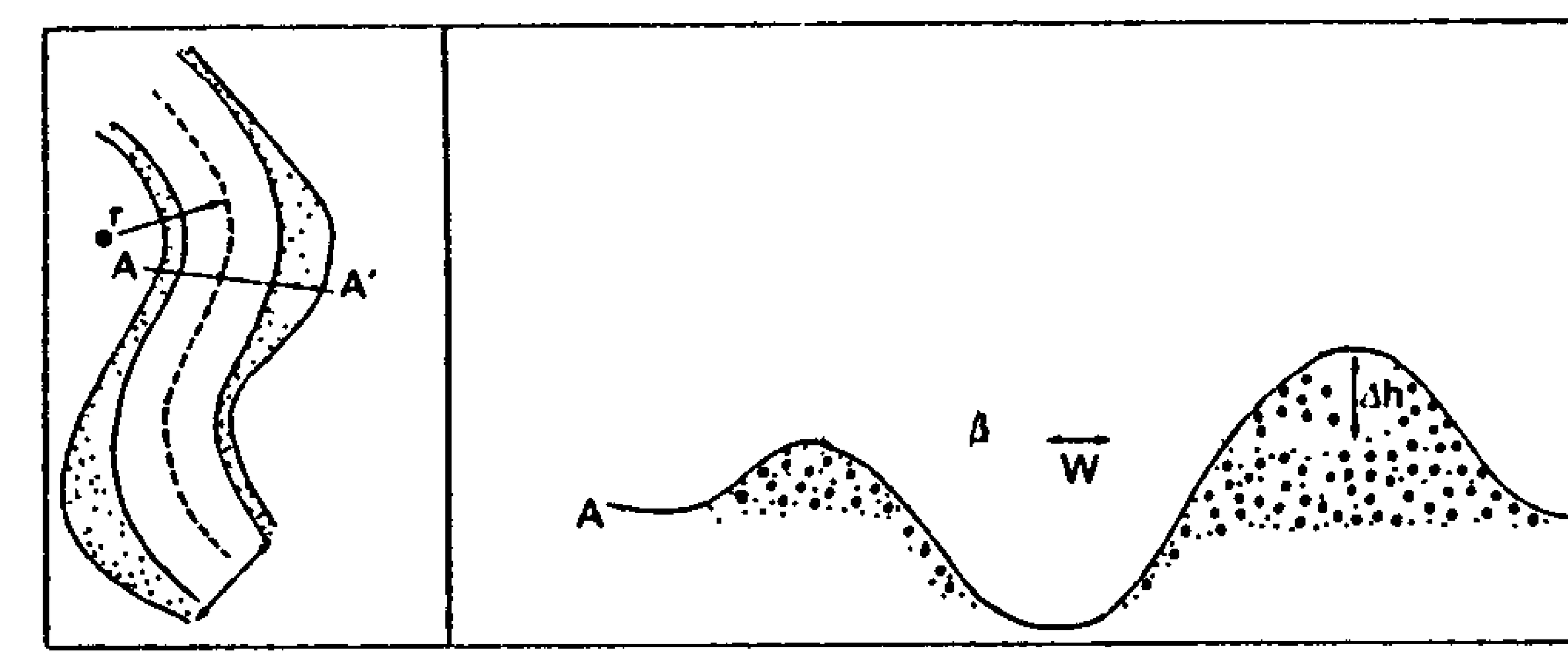
TORRENTS (Sheet 3)

FLOW TRACK ZONE

LEVEES/TRACK	
Distance from start levee-	
GR.-	
Label on g. map-	
Paired (Y/N)-	
Overall	
Start alt RB/ LB +angle-	
End alt RB/ LB + angle-	
Width when dep. Start-	
Length (Levee & track)-	
Number of breaks-	
Length of breaks-	
Mega-clast size & frequency-	
Velocity/ Discharge	
Radius of curvature-	
Flow width-	
Channel slope-	
SupElev angle & height	
Channel cross section-	
Extras	
Slope angle inner/ outer RB-	
Slope angle inter/ outer LB -	
Channel depth-	
Erosion depth-	
Scour or original surface ?	
Mat storage (Volume in xs)-	
Sedimentology (sep. sheet)	
Lichenometry (sep. sheet)	



W Width of flow
D Channel depth
H Levee height
D-H Erosion depth
SI Channel-side slope of levee
SO Outer slope of levee
16-18 Observation points
22°, 21° Channel slope angle between two observation points



r Radius of curvature
W Width of flow (cf. Fig.2)
Δh Difference in height between inner and outer levee
$\tan\beta$ Δh/W

Velocity/ Discharge	
Radius of curvature-	
Flow width-	
Channel slope-	
SupElev angle & height	
Channel cross section-	
Extras	
Slope angle inner/ outer RB-	
Slope angle inter/ outer LB -	
Channel depth-	
Erosion depth-	
Scour or original surface ?	
Mat storage (Volume in xs)-	
Sedimentology (sep. sheet)	
Lichenometry (sep. sheet)	

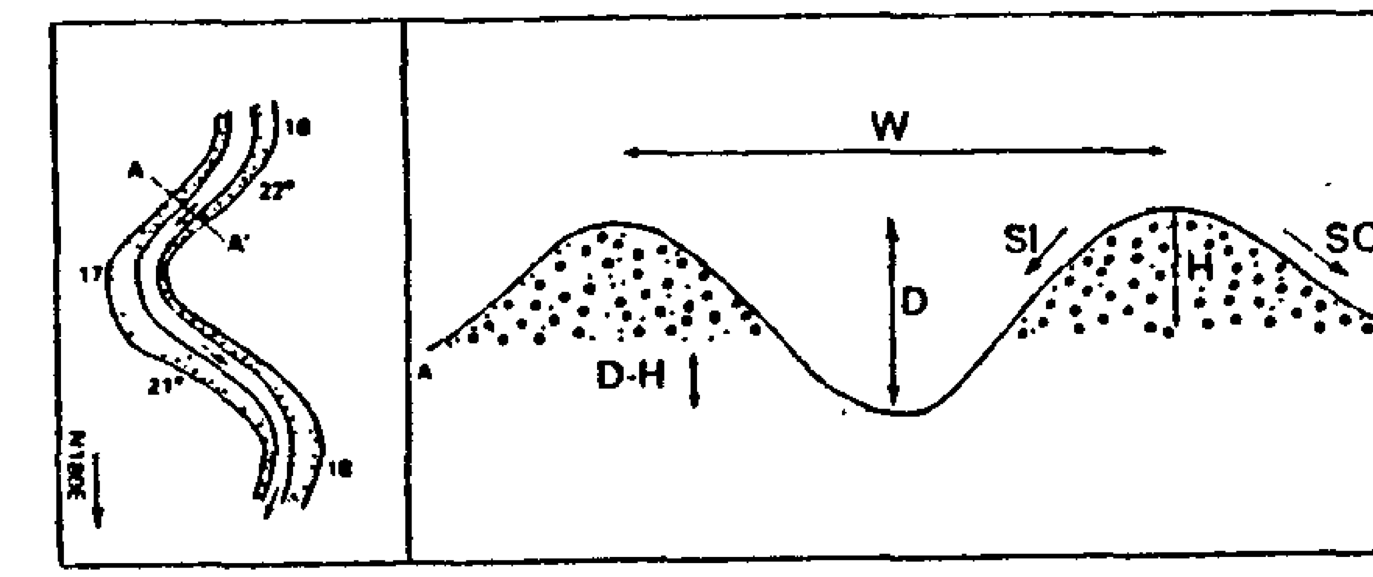
TORRENTS (Sheet 4)

STARTING ZONE/ SEDIMENT SOURCES

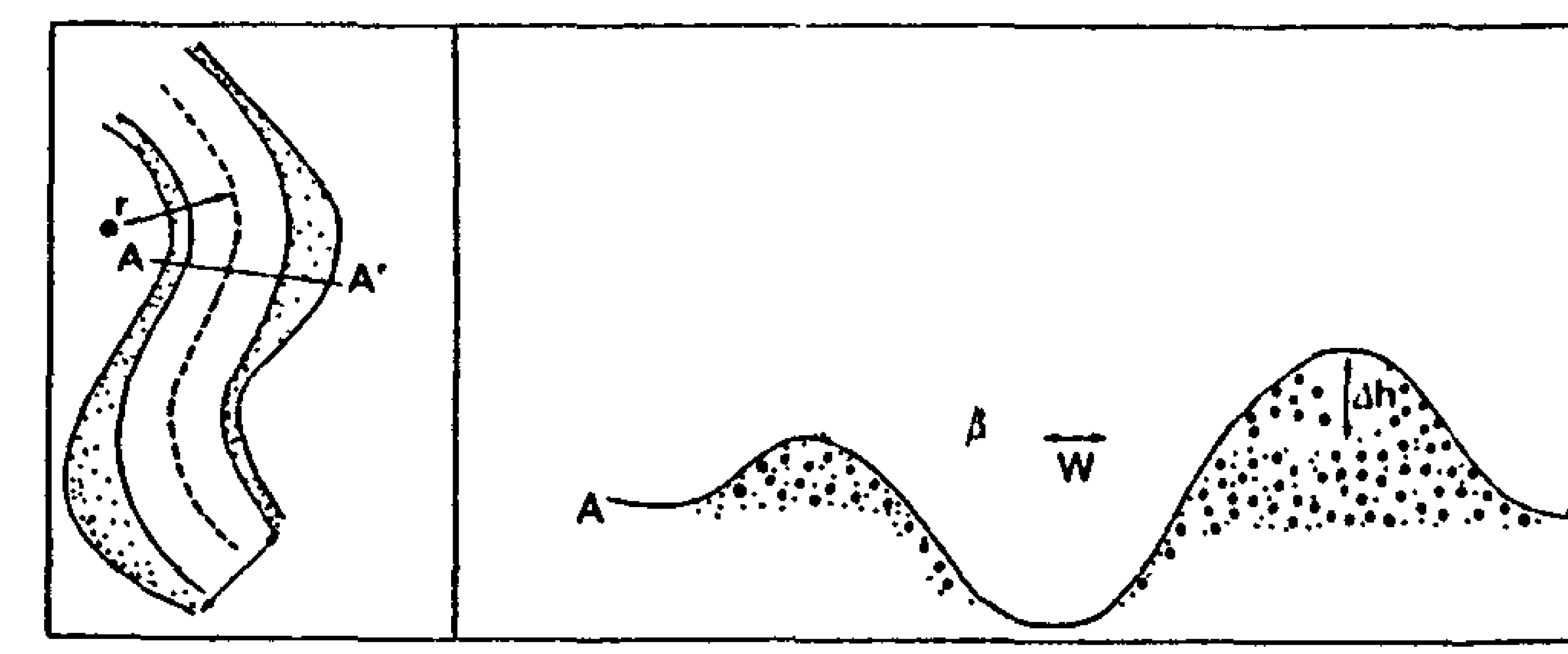
What sort feature-		What sort feature-		What sort feature-	
Location		Location		Location	
GR.		GR.		GR.	
Label on g. map-		Label on g. map-		Label on g. map-	
Morphometry		**Morphometry**		**Morphometry**	
max. Width		max. Width		max. Width	
max. Length-		max. Length-		max. Length-	
Depth (many)-		Depth (many)-		Depth (many)-	
Area (dis & angle)-		Area (dis & angle)-		Area (dis & angle)-	
Volume-		Volume-		Volume-	
Aspect-		Aspect-		Aspect-	
Altitude (Max/Min)-		Altitude (Max/Min)-		Altitude (Max/Min)-	
Slope-		Slope-		Slope-	
Sedimentology		**Sedimentology**		**Sedimentology**	
Material type-		Material type-		Material type-	
Stratigraphy (Separate sheet)-		Stratigraphy (Separate sheet)-		Stratigraphy (Separate sheet)-	
Sediment sample-		Sediment sample-		Sediment sample-	
Mat. strength		**Mat. strength**		**Mat. strength**	
Drainage (Y/N ?)		**Drainage (Y/N ?)**		**Drainage (Y/N ?)**	
Vegetation (Y/N ?)		**Vegetation (Y/N ?)**		**Vegetation (Y/N ?)**	
Material storage		**Material storage**		**Material storage**	
Volume-		Volume-		Volume-	
Material type-		Material type-		Material type-	
Age-		Age-		Age-	
Evidence of current stability		**Evidence of current stability**		**Evidence of current stability**	

TORRENTS (Sheet 5)

FAN	comprehensive
General morphometry	
Area-	
Max altitude-	
Min altitude-	
Max length-	
Max width-	
Slope angle-	
Slope description (p, vex,cav)	
Aspect-	
Sedimentology (plan only) (Separate sheet)	
Lichenometry (map loc)	
Vegetation- extent, damage	
Drainage	
LEVEES (id on map)	
Use above criteria	
magnitude(depth/area)	
LOBES (id on map)	
Morphometry	
Length-	
Width (many)-	
Depth (many)-	
Area (distance/angle)	
Side angles (RB/LB)-	
Toe angle-	
SHEET/BAR DEP.	
Length-	
Width (many)-	
Depth (many)-	
Area (distance/angle)	



W Width of flow
D Channel depth
H Levee height
D-H Erosion depth
SI Channel-side slope of levee
SO Outer slope of levee
16-18 Observation points
22°, 21° Channel slope angle between two observation points



r Radius of curvature
W Width of flow (cf. Fig.2)
Δh Difference in height between inner and outer levee
tanβ Δh/W

LEVEES (id on map)	
Use above criteria	
magnitude(depth/area)	
LOBES (id on map)	
Morphometry	
Length-	
Width (many)-	
Depth (many-	
Area (distance/angle)	
Side angles (RB/LB)-	
Toe angle-	
SHEET/BAR DEP.	
Length-	
Width (many)-	
Depth (many)-	
Area (distance/angle)	

HILLSLOPE DEBRIS FLOWS (Sheet 1)

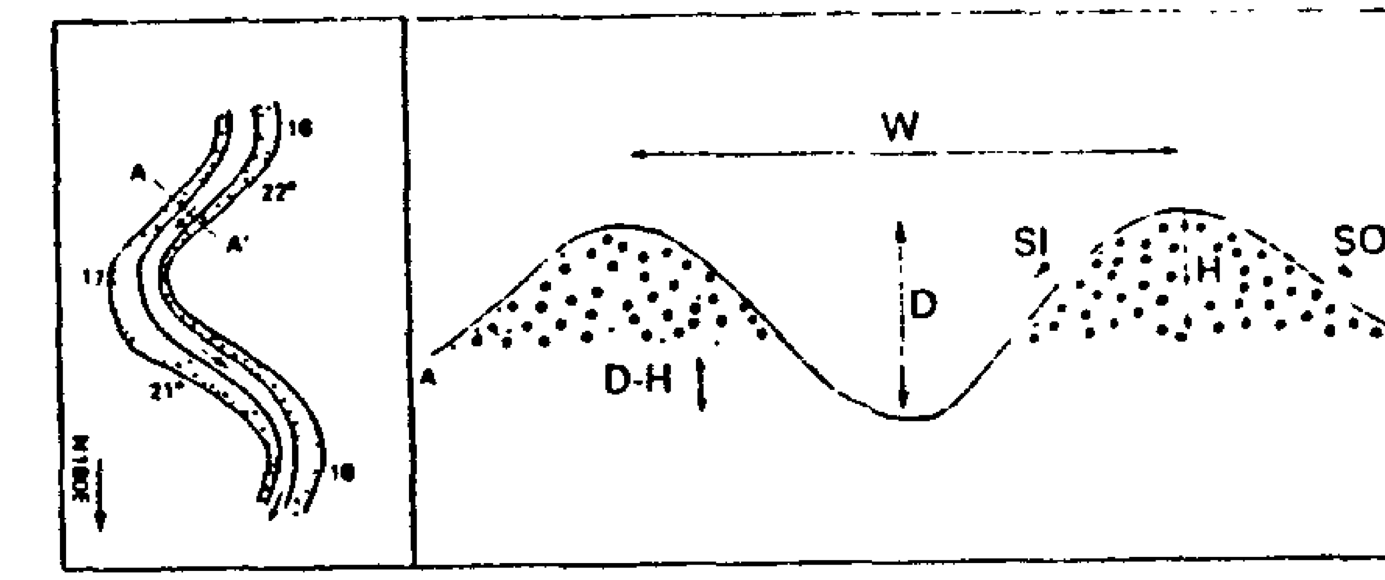
STARTING ZONE/ SEDIMENT SOURCES

What sort feature-		What sort feature-		What sort feature-	
Location		Location		Location	
GR.		GR.		GR.	
Label on g. map-		Label on g. map-		Label on g. map-	
Morphometry		**Morphometry**		**Morphometry**	
max. Width		max. Width		max. Width	
max. Length-		max. Length-		max. Length-	
Depth (many)-		Depth (many)-		Depth (many)-	
Area (dis & angle)-		Area (dis & angle)-		Area (dis & angle)-	
Volume-		Volume-		Volume-	
Aspect-		Aspect-		Aspect-	
Altitude (Max/Min)-		Altitude (Max/Min)-		Altitude (Max/Min)-	
Slope-		Slope-		Slope-	
Sedimentology		**Sedimentology**		**Sedimentology**	
Material type-		Material type-		Material type-	
Stratigraphy (Separate sheet)-		Stratigraphy (Separate sheet)-		Stratigraphy (Separate sheet)-	
Sediment sample-		Sediment sample-		Sediment sample-	
Mat. strength		**Mat. strength**		**Mat. strength**	
Drainage (Y/N ?)		**Drainage (Y/N ?)**		**Drainage (Y/N ?)**	
Vegetation (Y/N ?)		**Vegetation (Y/N ?)**		**Vegetation (Y/N ?)**	
Material storage		**Material storage**		**Material storage**	
Volume-		Volume-		Volume-	
Material type-		Material type-		Material type-	
Age-		Age-		Age-	
Evidence of current stability		**Evidence of current stability**		**Evidence of current stability**	

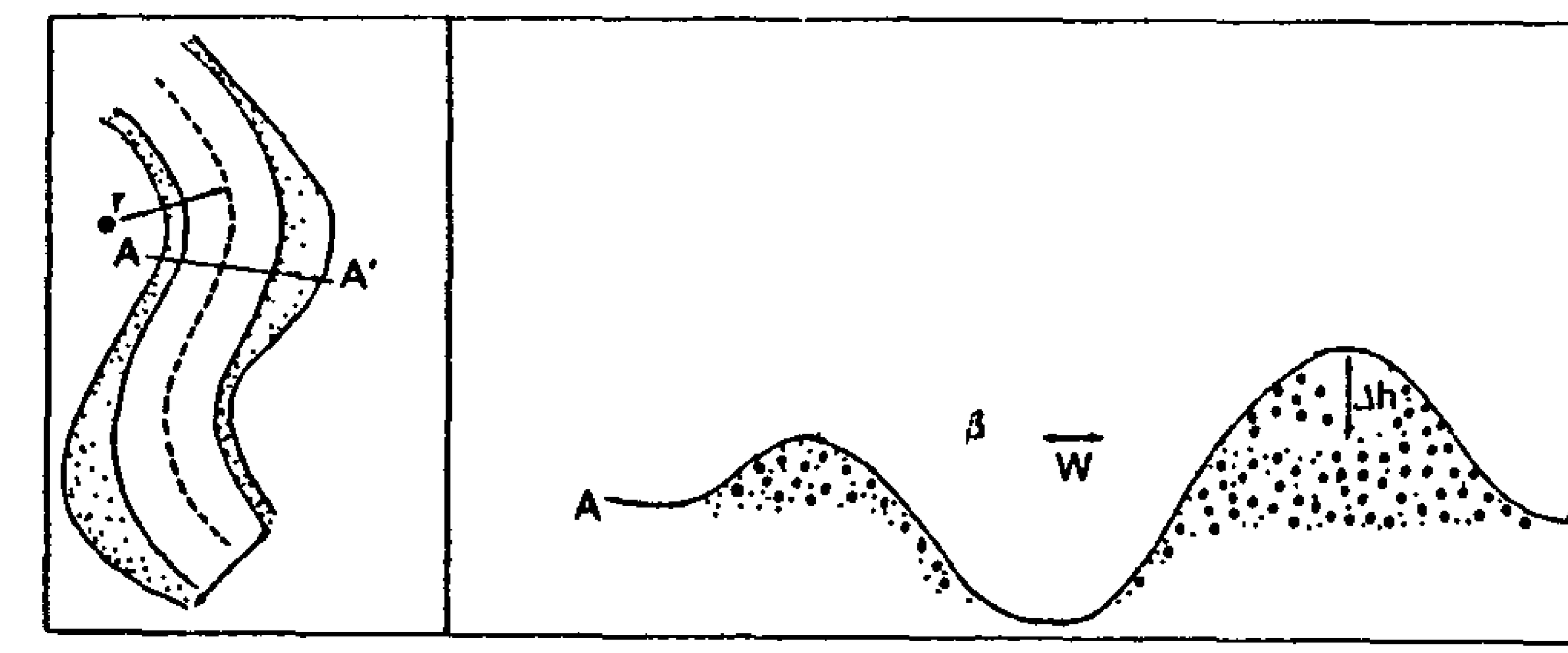
HILLSLOPE DEBRIS FLOWS (Sheet 2)

FLOW TRACK ZONE

LEVEES/TRACK	
Distance from start levee-	
GR.-	
Label on g. map-	
Paired (Y/N)-	
Overall	
Start alt RB/ LB +angle-	
End alt RB/ LB + angle-	
Width when dep. Start-	
Length (Levee & track)-	
Number of breaks-	
Length of breaks-	
Mega-clast size & frequency-	
Velocity/ Discharge	
Radius of curvature-	
Flow width-	
Channel slope-	
SupElev angle & height	
Channel cross section-	
Extras	
Slope angle inner/ outer RB-	
Slope angle inter/ outer LB -	
Channel depth-	
Erosion depth-	
Scour or original surface ?	
Mat storage (Volume in xs)-	
Sedimentology (sep. sheet)	
Lichenometry (sep. sheet)	



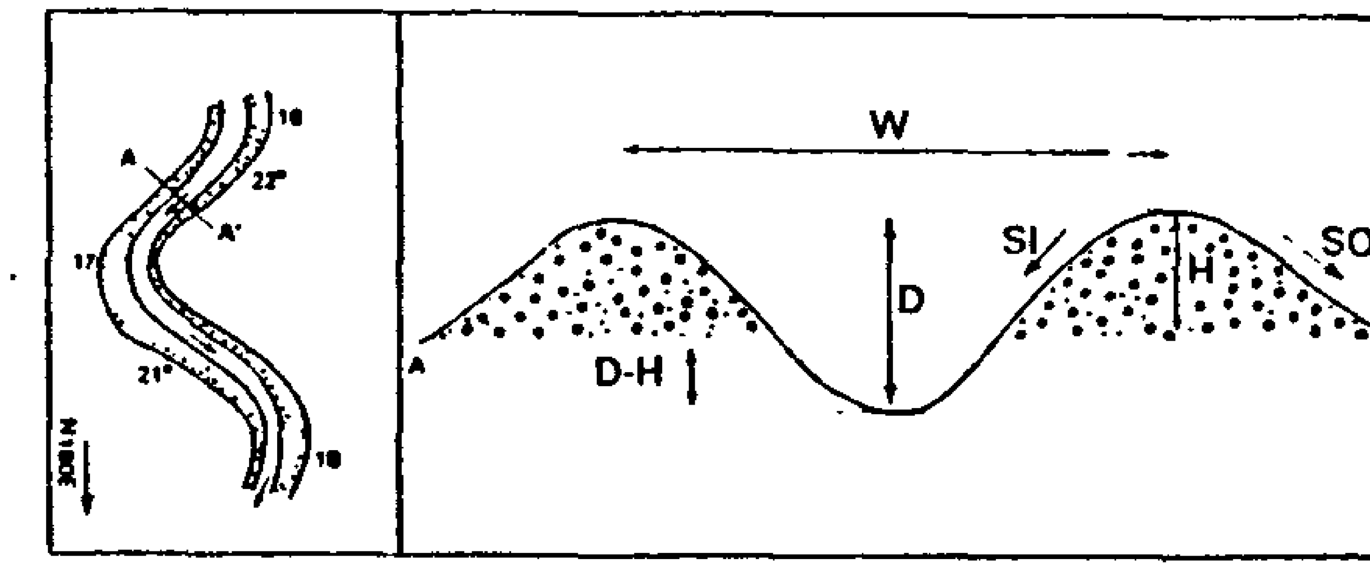
W Width of flow
D Channel depth
H Levee height
D-H Erosion depth
SI Channel-side slope of levee
SO Outer slope of levee
16-18 Observation points
22°, 21° Channel slope angle between two observation points



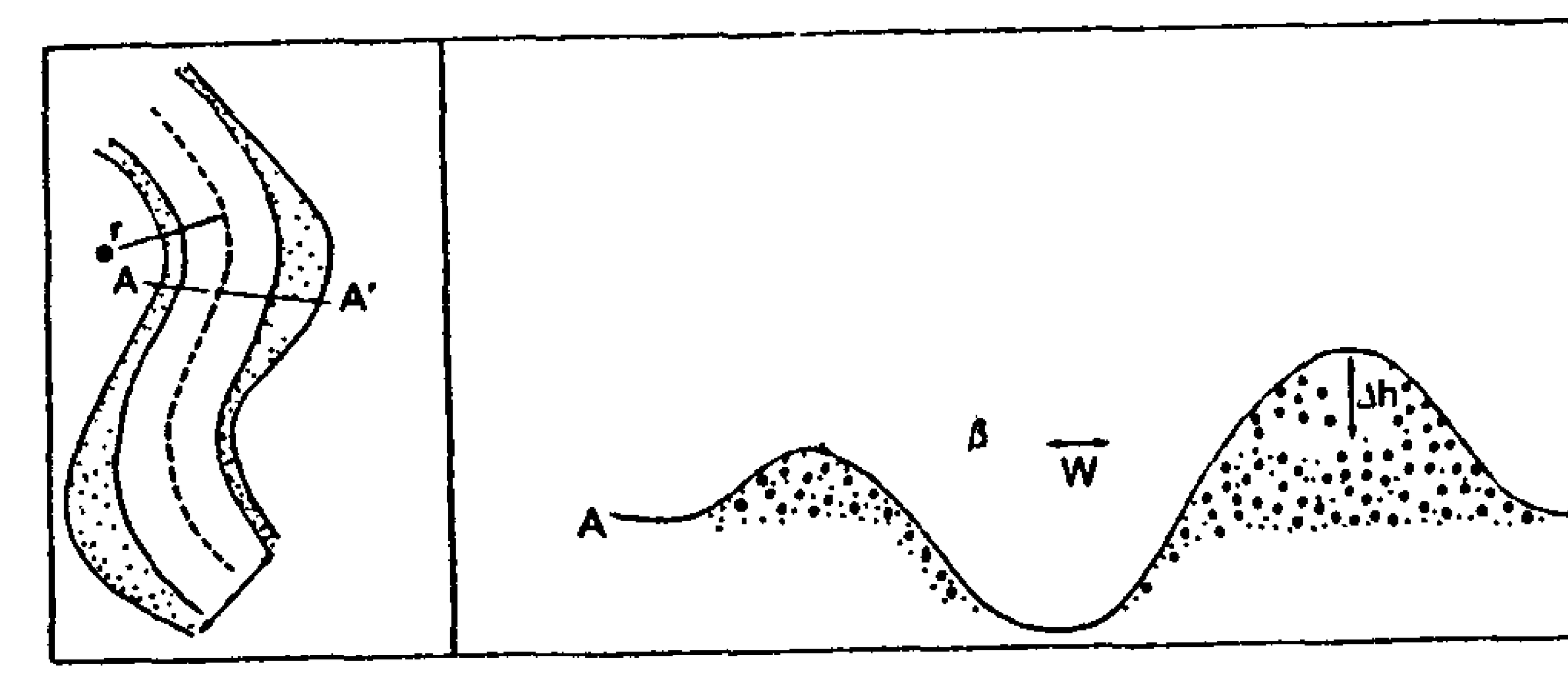
r Radius of curvature
W Width of flow (cf. Fig.2)
Δh Difference in height between inner and outer levee
tanβ Δh/W

Velocity/ Discharge	
Radius of curvature-	
Flow width-	
Channel slope-	
SupElev angle & height	
Channel cross section-	
Extras	
Slope angle inner/ outer RB-	
Slope angle inter/ outer LB -	
Channel depth-	
Erosion depth-	
Scour or original surface ?	
Mat storage (Volume in xs)-	
Sedimentology (sep. sheet)	
Lichenometry (sep. sheet)	

HILLSLOPE DEBRIS FLOWS (Sheet 3)



W Width of flow
D Channel depth
H Levee height
D-H Erosion depth
SI Channel-side slope of levee
SO Outer slope of levee
16-18 Observation points
22°, 21° Channel slope angle between two observation points



r Radius of curvature
W Width of flow (cf. Fig.2)
Δh Difference in height between inner and outer levee
tanβ Δh/W

DEPOSITIONAL ZONE

FAN	
General morphometry	
Area-	
Max altitude-	
Min altitude-	
Max length-	
Max width-	
Slope angle-	
Slope description (p, vex,cav)	
Aspect-	
Sedimentology (plan only) (Separate sheet)	
Lichenometry (map loc)	
Vegetation- extent, damage	
Drainage	
LEVEES (id on map)	
Use above criteria	
Magnitude(depth/area)	
LOBES (id on map)	
Morphometry	
Length-	
Width (many)-	
Depth (many)-	
Area (distance/angle)	
Side angles (RB/LB)-	
Toe angle-	

LEVEES (id on map)	
Use above criteria	
magnitude(depth/area)	
LOBES (id on map)	
Morphometry	
Length-	
Width (many)-	
Depth (many-	
Area (distance/angle)	
Side angles (RB/LB)-	
Toe angle-	

Date: Observer: Location: G.R.: Altitude: Aspect:

State of exposure:

Depth & marker number	Sed. Size (field or lab)	Matrix content (clst. Or mat. Sup)	Sed. Roundness	Sed structure a. grading b. imbrication c. sorting	Type of contact	Organics	Samples	Photo

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